The Journal of

THE ROYAL AERONAUTICAL SOCIETY

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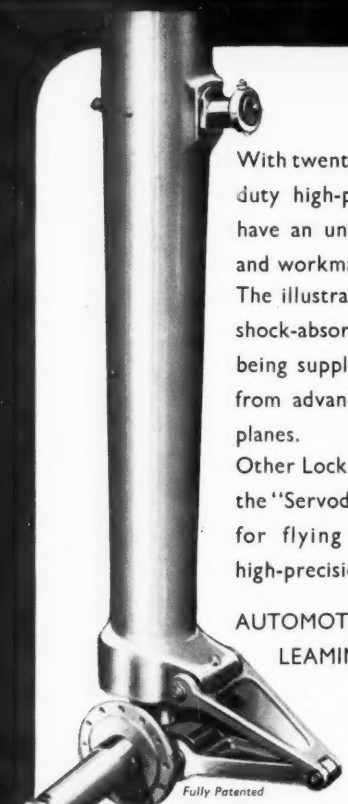

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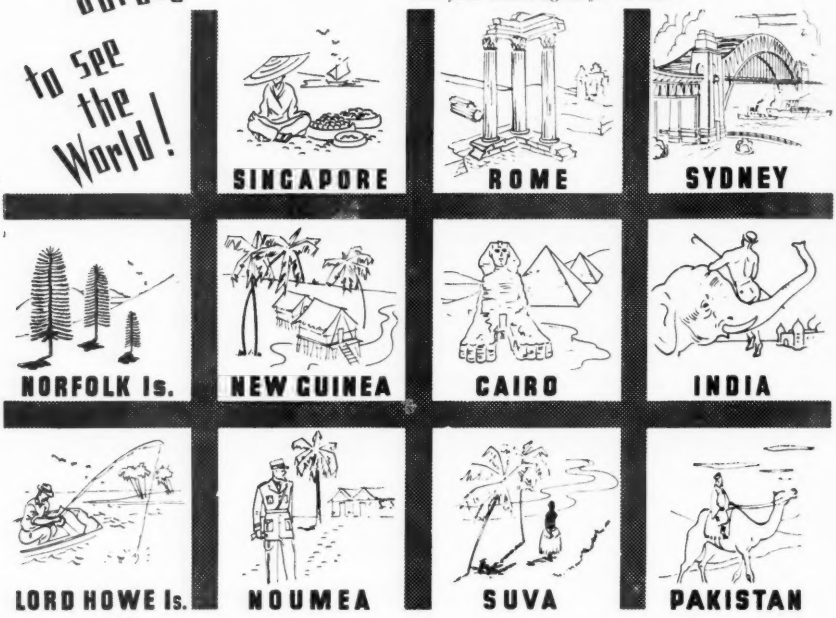

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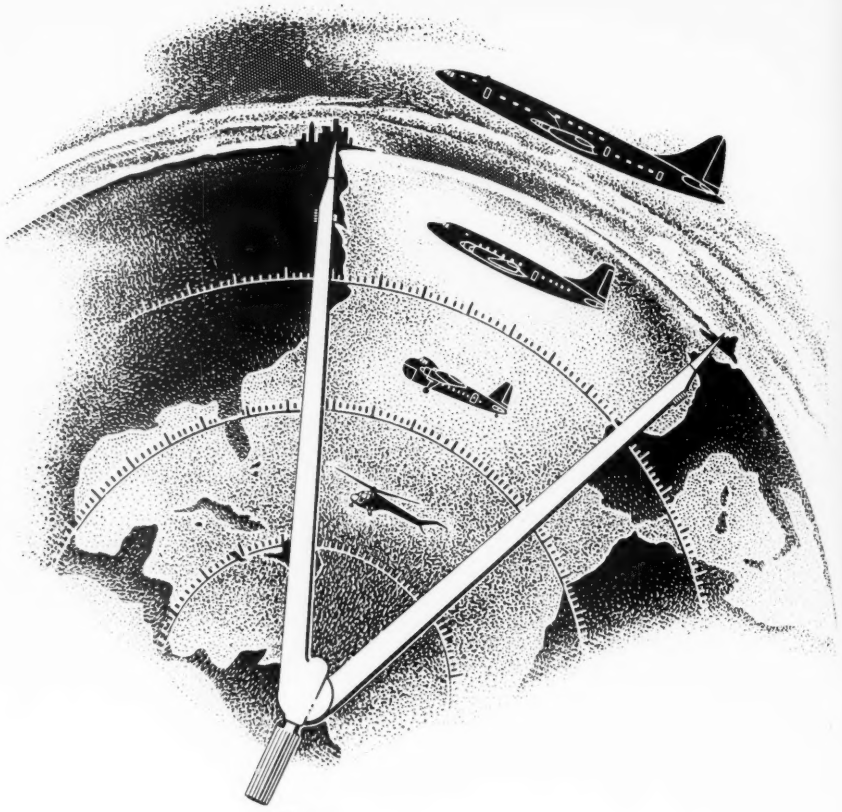

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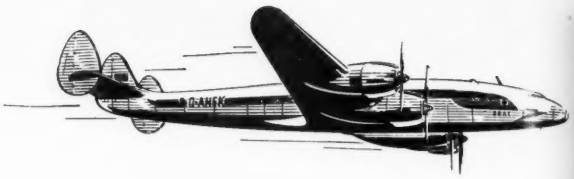

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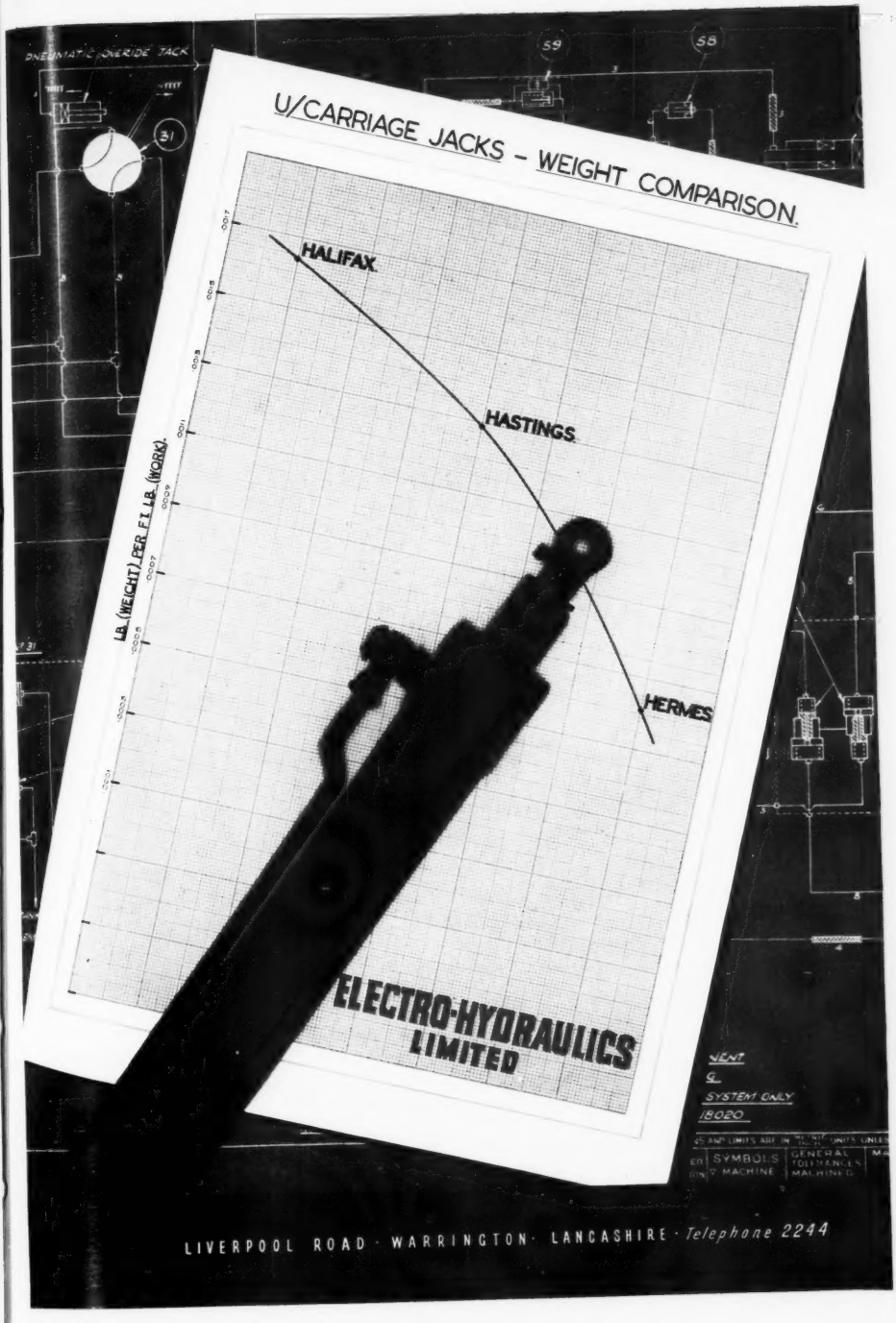
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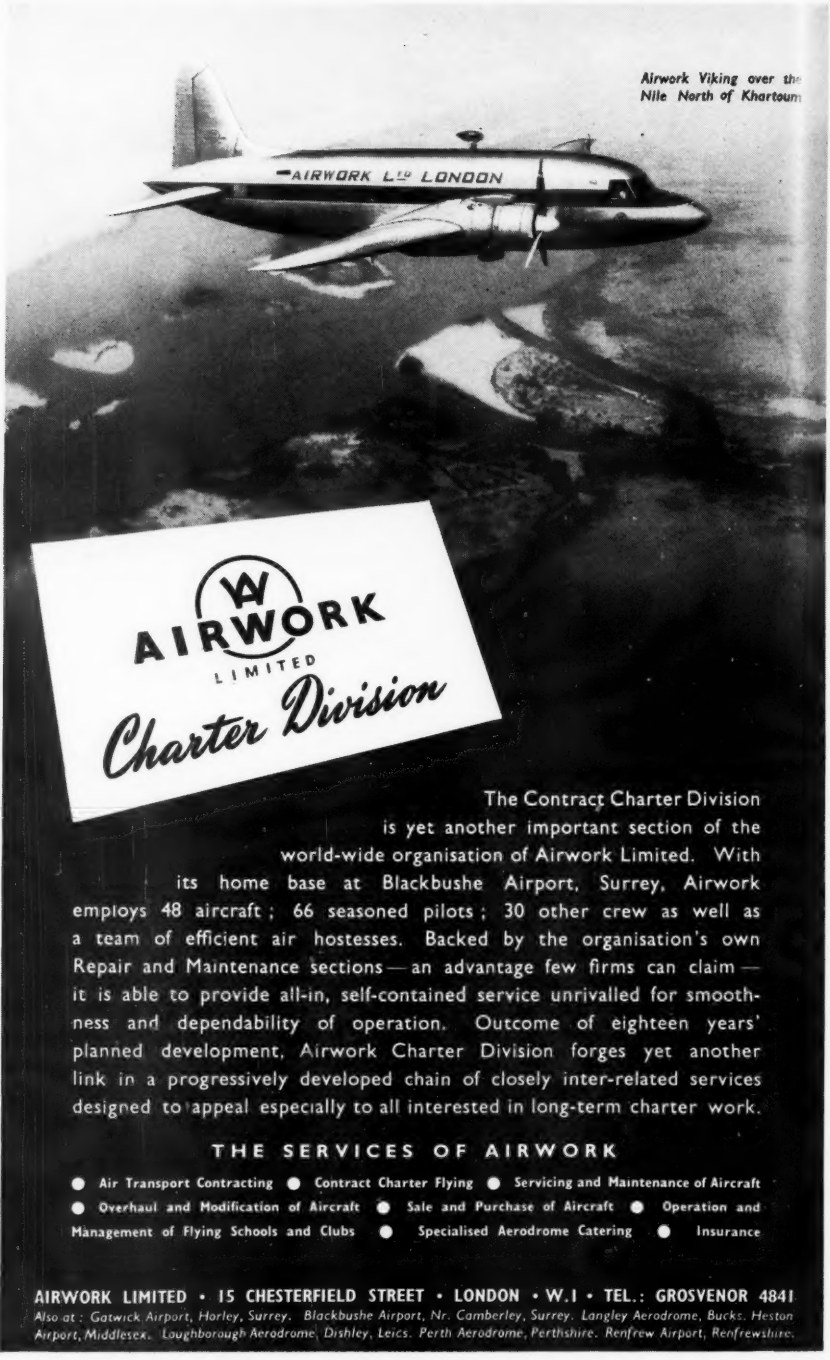

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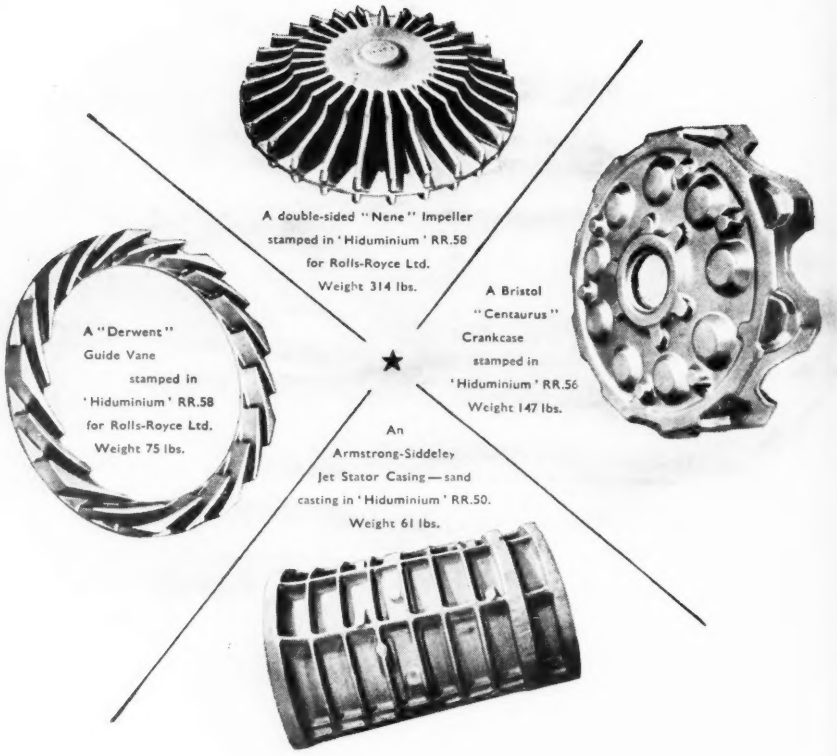
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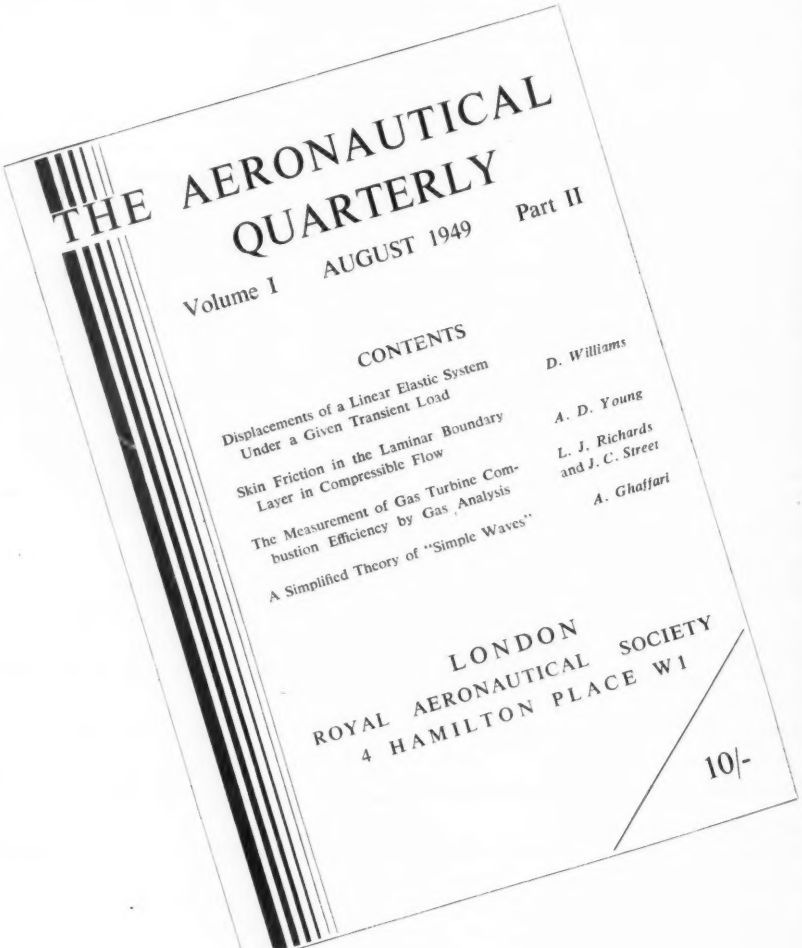
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THE DESIGN OF PROPELLERS

by

G. C. I. GARDINER, A.F.R.Ae.S.

and

J. MULLIN, B.Sc.(Eng.), A.F.R.Ae.S.

The 773rd Lecture was read before the Society on the 17th March 1949 at the Institution of Civil engineers, Great George Street, S.W.1. Dr. H. Roxbee Cox, B.Sc., D.I.C., F.R.Ae.S., F.I.Ae.S., President of the Society, introduced the lecturers, Mr. G. C. I. Gardiner, A.F.R.Ae.S., Chief Engineer and Mr. J. Mullin, B.Sc., A.F.R.Ae.S., Chief Aerodynamicist of de Havilland Propellers Ltd.

Opening the meeting the Chairman said there was a time when all power-driven aircraft had to have propellers. That unique situation had come to an end in 1939 and since then there had been people who prophesied that a flourishing propeller industry would go out of business. In fact, that was nonsense and it was evident that, except for aeroplanes of the highest performance, the propeller would be with them and of great importance indeed for many years to come.

1. INTRODUCTION

In the past there have been several papers, attempting, with varying degrees of success, to predict the future trends of propeller design, but not many concerning the more practical aspects of propeller design as it is today.

The object of the present paper is to dispel certain illusions and uncertainties and to disseminate as widely as possible the present methods and viewpoints of the propeller designers in this country.

Despite the technical arguments which rage from time to time on the relative merits of propeller and jet propulsion, it remains a fact that the pure jet is replacing the propeller in the field of high speed military aircraft. For this reason, and to avoid a rather vague discussion covering a very wide field, the authors have limited this paper to a consideration of propeller design for transport aircraft.

As far as possible the paper avoids the discussion of any one particular type of propeller, but in some cases this has not been possible, so that detailed comments have had to be limited to the type of hydraulically-operated propeller with which the authors are most familiar.

2. PROPELLER EFFICIENCY AND THRUST

The primary purpose of a propeller is to produce thrust and to do this efficiently considerable co-operation is necessary between the aircraft engine and propeller designers.

Without a means of measuring the engine shaft horse power, or the propulsive thrust in flight, there is no satisfactory method of separating the airframe, engine and propeller performance, although the advent of torque meters has now enabled the engine performance in flight to be accurately assessed.

For this reason, coupled with the fact that it is difficult to estimate the effect of the propeller slipstream on the aeroplane drag, aircraft designers are more concerned with the performance of a propeller relative to one on which they have had experience, perhaps on a previous aircraft design, than with the absolute figure of efficiency quoted by the propeller designer.

It is desirable to know the absolute value of propeller efficiency to a reasonable degree of accuracy, but it is more important to obtain strictly comparable performance quotations from all possible sources.

A great step in this direction has recently been achieved by the British propeller firms who have worked together for the past six

years as an S.B.A.C. Panel to produce a method of propeller performance estimation which they are all content to use.[1]

By this means it is possible to choose rapidly the best diameter, number and area of blades, together with the most suitable r.p.m. for a given aircraft design. Nevertheless, when a new blade design is considered for a specific application it is sometimes necessary to turn to one of the more laborious and detailed methods of strip analysis, most of which differ only in their finer points and owe a great deal to the work of C. N. H. Lock.[2] Perhaps the greatest value of such methods to the propeller industry has been their ability to explain the mechanism of propeller thrust production, and to make clear the effect of the separate variables involved.

To appreciate some of the later parts of the paper, it is necessary at this stage to consider the factors controlling propeller efficiency. This can be considered as the product of an "induced" and a "profile efficiency."

The induced efficiency at a given operating condition is mainly a function of disc loading (SHP/D^2) and falls as the loading is increased (see Fig. 1).

Profile efficiency is primarily affected by the lift/drag ratio of the blades which, in turn, is controlled by the blade incidence and hence by the propeller blade area (see Fig. 2).

3. PROPELLER DIAMETER

Without doubt this is the most important propeller design parameter, and it cannot be emphasised too strongly that, with freedom to choose both blade area and r.p.m., the larger propeller will always give the higher efficiency. This should be immediately apparent from Figs. 1 and 2, where the highest induced efficiency is obtained from the lowest value of (SHP/D^2) while the highest value of profile efficiency is obtained by choosing the blade area to obtain the highest value of lift/drag ratio.

There are naturally many reasons which make the final choice of diameter a compromise: the final decision must inevitably be made by the aircraft designer, since he alone can assess the relative merits of a larger diameter of propeller against the inevitable increase in weight of undercarriage needed to provide ground clearance for the propeller. The desire to reduce the offset thrust in case of engine failure, also discourages the use of large diameter propellers which must be positioned farther from the centre line of the aircraft.

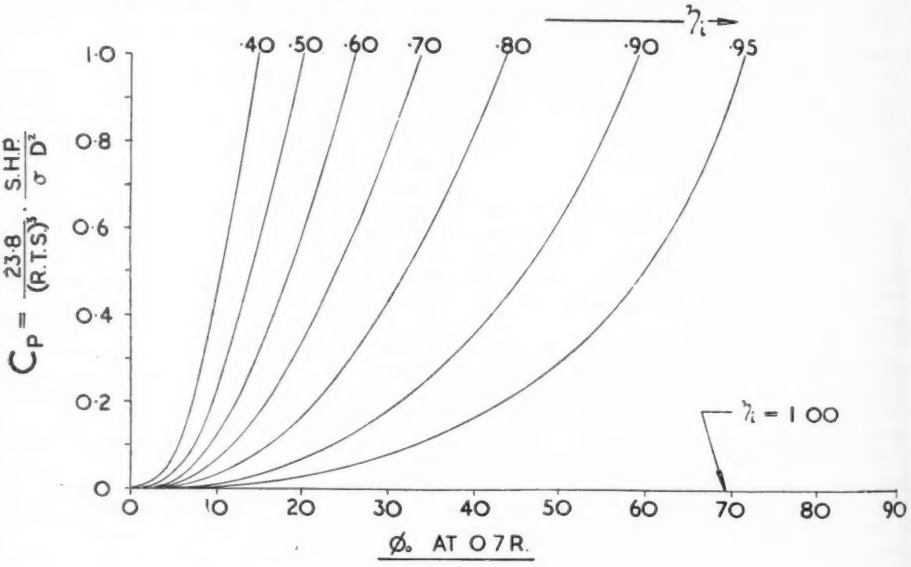

Fig. 1.
Variation of induced efficiency with power loading and angle of advance (ϕ_0).

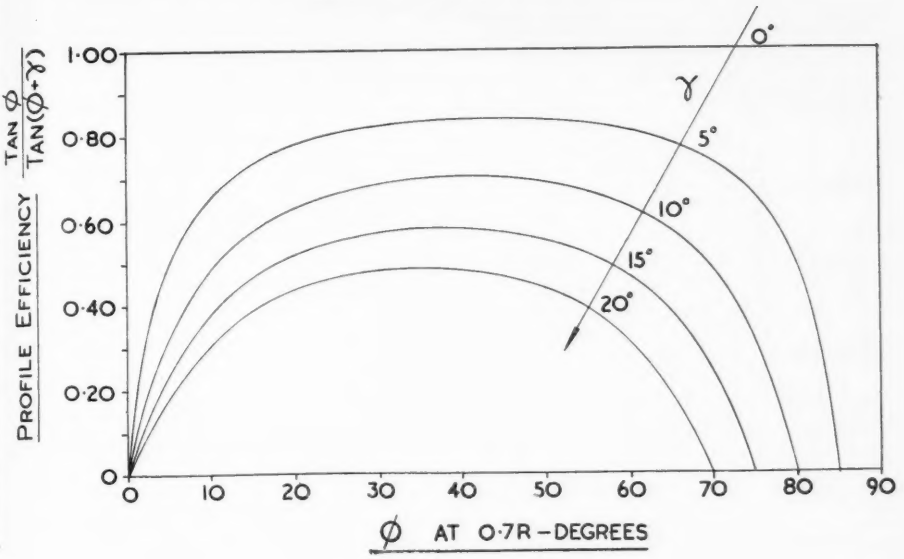

Fig. 2.
Variation of profile efficiency with angle of advance and γ.

$$\text{Tan } \gamma = \frac{\text{Drag}}{\text{Lift}}$$

The following effects can be expected on installations where the propeller has been severely limited in diameter:

(*a*) Loss of thrust efficiency both at take-off and cruising at low r.p.m.

(*b*) Increase in noise level because of the use of relatively higher tip speeds in an attempt to recover some of the performance lost by the small diameter.

(*c*) Contrary to expectations the reduction of propeller diameter can, in certain circumstances, result in a considerable increase in propeller weight.

The choice of gear ratio depends almost entirely on the available propeller diameter and limiting tip speed. For the purpose of predicting propeller diameter an empirical curve has been established based on previous experience, showing variation of diameter with shaft horse power, as shown in Fig. 3.

A first estimate of propeller diameter is usually made by means of a curve such as this and the result checked by more specific investigations of future designs.

If Fig. 3 is studied in some detail several interesting points will become apparent. Boundary curves have been added to the group of points on the figure and have been labelled "Initial SHP" and "Final SHP."

When a new engine appears it can be assumed that over the course of some years its power output will increase perhaps by as much as 50 per cent., so that, when choosing a propeller diameter it is as well to bear this in mind.

Higher disc loadings (SHP/D^2) can be usefully employed as aircraft speed and range increase and it is this effect, and not the desire of aircraft designers to limit diameter at the expense of performance, that is portrayed on this curve.

4. PROPELLER NOISE AND ROTATIONAL TIP SPEED

Since we are considering transport aircraft, it is propeller noise emission at the operating cruising condition rather than the adverse effects of compressibility, that determines the limiting tip speed at which the propeller should be operated.

Several tests have been conducted to measure the noise created by a propeller, but few have been made to measure the noise level inside the aircraft in flight.

One of the most useful and comprehensive of these[3] bears out to a large extent the rule derived from operating experience, that cruising rotational tip speeds above 700 feet per second will result in an excessive noise

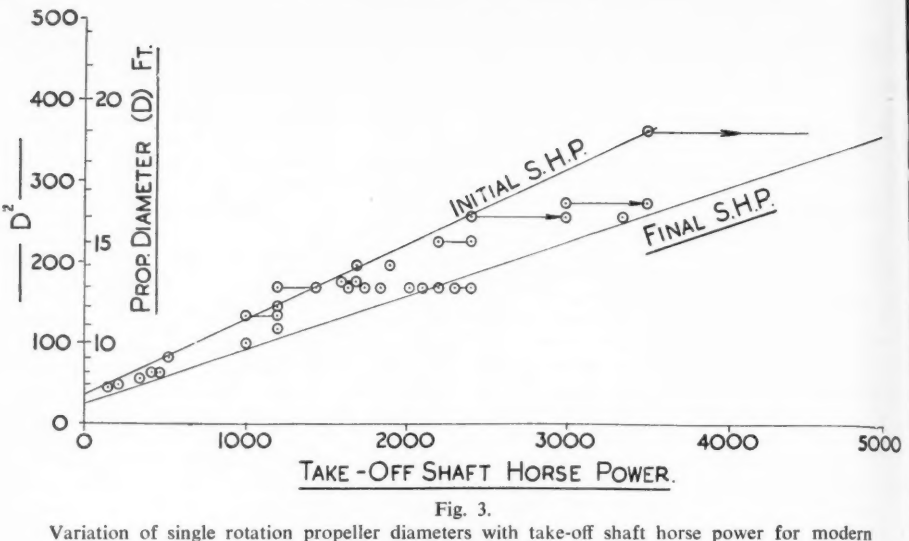

Fig. 3.
Variation of single rotation propeller diameters with take-off shaft horse power for modern transport aircraft.

level. This report shows that the noise level in an aircraft cabin increases with tip speed, power per blade and reduction of propeller tip-fuselage clearance.

The number of blades carried by a propeller is usually determined by more immediate considerations than propeller noise. The tip-fuselage clearance is in the hands of the aircraft designer and should not be less than about 12 inches, so that the only course open to the propeller designer is to limit the cruising rotational tip speed to about 700 ft./sec.

On piston engines this process is satisfactory, giving tip speeds at take-off rating of 900 to 1,000 ft./sec. which is just about the limit set by compressibility effects.

On the type of gas turbine engine where the compressor and turbine are geared to the propeller shaft, it is economical to cruise at 90 to 95 per cent. of maximum r.p.m. so that it is necessary either to increase the cruising tip speed and tolerate more noise, or sacrifice take-off thrust resulting from the low tip speed in this condition.

5. PROPELLER BLADE AREA AND OTHER FACTORS

When the propeller diameter and r.p.m. have been fixed by the aircraft design and engine gear ratio, the induced efficiency is to a great extent determined for a given flight condition. It is true that the number of blades and the distribution of loading along the blades both have their effect upon induced efficiency, but this is only of the order of one per cent. and at this stage can be neglected. The skill of the designer therefore can only be exercised in choosing the blade area in order to operate at the most suitable lift/drag ratio.

Figure 4 shows a typical variation of cruise, climb and take-off efficiency with blade area solidity and from this it will be seen that the value chosen must be a compromise between a small area to give the maximum cruising efficiency and a larger area giving the best take-off thrust.

In this example, to reach a compromise it has been necessary to sacrifice about one per cent. of cruise and about four per cent. of take-off efficiency.

Number of blades

Up to this point little has been said about the number of blades in a propeller because, in fact, this is governed by the more practical consideration of weight and the hub type available, rather than for reasons of aerodynamic performance.

Blade aerofoil sections

In the early days of fixed-pitch propellers the range and endurance of aircraft were small, so that the ratio of fuel load to payload was lower than is common today. For

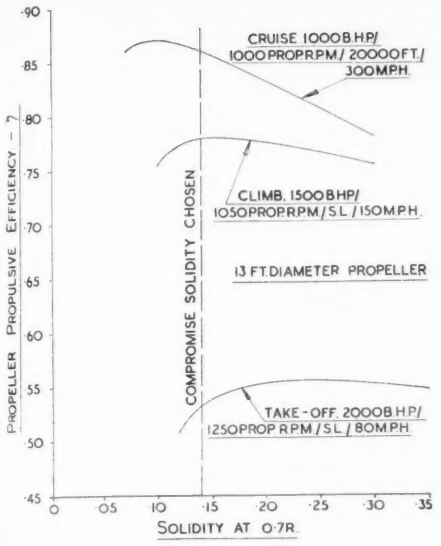

Fig. 4.

Typical variation of propeller propulsive efficiency with solidity for a piston-engined transport aircraft.

this reason, the accent on propeller performance was placed on the conditions of take-off and climb rather than on cruising efficiency. It was quite natural and correct therefore, that the propeller designers should choose variations of R.A.F.6 as an aerofoil section having good stalling characteristics and a reasonable maximum lift/drag ratio.

With the advent of the variable-pitch propeller the take-off problem became easier and the range of aircraft increased, thereby increasing interest in cruising efficiency. These trends called for a propeller aerofoil section with a better maximum value of lift/drag ratio and led to the use of the Clark Y (modified) section for propeller blades.

Early in 1940 the N.A.C.A. produced their Series 16 sections designed to mitigate compressibility effects, but which also had the advantage of a higher maximum lift/drag ratio than the Clark Y sections. At first it was thought that these sections would not be of interest to propeller designers, since the stalling characteristics were poor with low camber sections. As more information was obtained it was found that with only a small sacrifice of lift/drag ratio, a stalling characteristic comparable with that of a Clark Y section could be obtained by using a Series 16 section cambered to a design lift coefficient of about 0.5.

Thickness/chord ratio on blades incorporating Clark Y sections have been reduced to $6\frac{1}{2}$ per cent. over the operating portion of the blade and, although further reduction may save blade weight, it has an adverse effect on aerodynamic performance. With N.A.C.A. 16 sections, however, the thickness/chord ratio can be further reduced with advantage.

These sections with their maximum thickness at 50 per cent. chord are convenient for the design of certain types of hollow steel blade and are rapidly displacing the Clark Y sections in new propeller designs.

De-icing overshoes

From the aerodynamic performance viewpoint these overshoes, extending over about $\frac{2}{3}$ of the blade radius, produce a performance loss varying from about 2 per cent. at take-off to about 4 per cent. in the low powered cruise conditions near peak efficiency. These figures are worth comparing with the drop in efficiency of 13 to 14 per cent. due to the most severe icing imaginable.[4]

6. PROPELLER WEIGHT

The estimation and analysis of propeller weight is a difficult subject upon which to produce a generalised method, but the problem has been dealt with most satisfactorily on the basis suggested by McCoy.[5]

Figures 5 and 6 show two empirical curves, the one relating total blade weight as a fraction of bare propeller weight to number of blades, the other, blade weight to diameter and solidity. From these two curves graphs can be obtained to show generalised variations of propeller weight with diameter and number of blades for various solidities.

It can be seen that the curve showing blade weight is based on the weights at various diameters of a few blade designs labelled *A*, *B*, *C*, and so on, each having a different blade shank size, and it must be realised that the propeller manufacturer does not have an infinite variety of shank sizes but only these few basic designs and minor variants of them. Thus, discontinuous curves of propeller weight can be produced (see Fig. 7).

Sometimes an aircraft designer requests a propeller with somewhat wider blades than one which he already possesses and is surprised to be confronted with a large increase

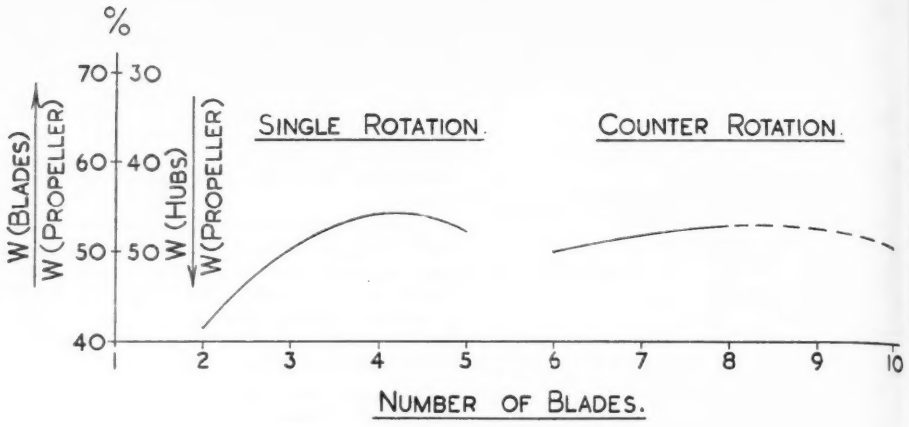

Fig. 5.
Variation of blade and hub weights, as percentages of total propeller weight, with number of blades. Dural blades.

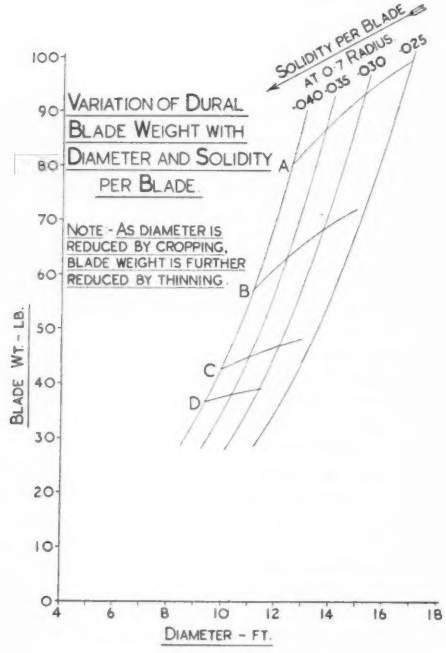

Fig. 6.

in weight; it may have been necessary to increase the blade shank size to carry the larger blade and the propeller weight increases accordingly to that of the next larger size.

The influence of propeller weight on the choice of number of blades is interesting. Using Figs. 5 and 6, the variation of propeller weight with number of blades can be obtained showing that a minimum weight is obtained by using four to five blades in a single rotation hub.

With hollow steel blades consisting of a tubular steel spar carrying a lightweight steel shell to form the aerofoil blade shape, the curve of Blade Weight/Propeller Weight is of somewhat different slope, the ratio being almost the same for three and four blades. Since wider blades can be obtained merely by increasing the chord of the thin steel shell, the variation in blade weight with blade area is not large and, for a given total blade area, the total blade weight rises appreciably with number of blades.

Therefore, a curve of propeller weight against number of blades for constant total blade area and diameter shows the smaller number of blades to be lighter: so that dural-bladed propellers tend to have larger numbers of medium width blades, while with hollow steel blades the tendency is towards smaller numbers of very wide blades.

With this consideration in view, to obtain the maximum blade area the tips of the steel blade are square, thereby adding blade area at its most effective radius.

In the above paragraphs, only bare propeller weights have been considered, that is, hub and blades alone. For modern transport aircraft this is only a portion of the

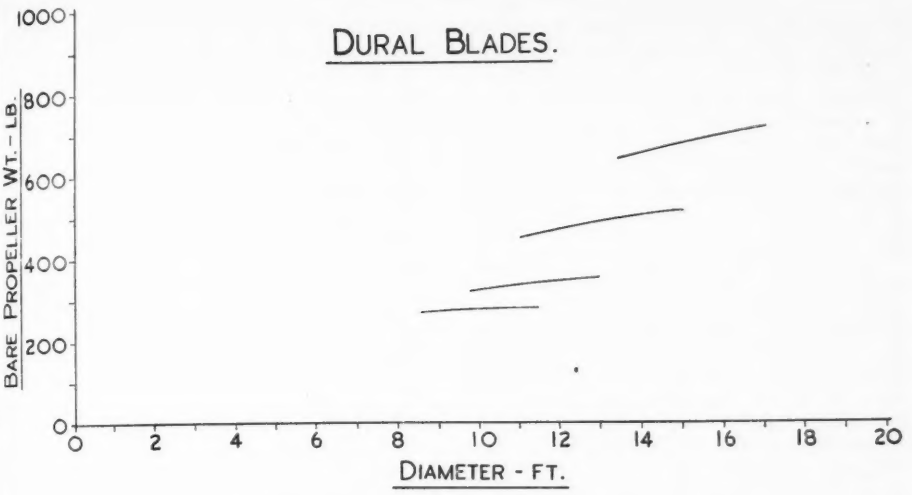

Fig. 7.
Variation of four-bladed propeller weight with diameter.

complete picture, since the weight of equipment which the propeller requires to perform its numerous functions amounts to an appreciable fraction of the bare propeller weight.

The following table shows a typical distribution of weight for the various items of propeller equipment:—

	% of installed propeller weight
Bare propeller	77.0
Constant speed unit ...	1.3
Feathering equipment ...	2.7
Spinner	6.9
Engine cooling fan* ...	7.6
Braking equipment ...	1.9
De-icing equipment ...	1.1
Miscellaneous controls, etc.	1.5
Installed dry weight ...	100%

*The cooling fan weight is more a function of the engine requirements than the propeller design.

On present-day installations the average specific weight of bare propellers is about 0.25 lb./SHP based on take-off power, so that the average installed specific weight will vary from this figure to about 0.33. These figures are reasonably representative of both piston engines and turbines, since the saving in weight on turbine installations which was expected to result from the reduction of engine vibration, has not completely materialised.

This is due to a better appreciation of the importance of aerodynamically excited vibration stresses, which are not altered by the change in the type of engine.

7. STANDARDISATION

So far in this paper, apart from one or two instances, various trends have been considered in a general manner, assuming that an infinite number of propeller designs existed and could be chosen to suit any particular aircraft design. Naturally this is not the case, since development costs and the necessity for some degree of standardisation in production force the designer to limit himself to a standard series of basic designs to cover the range of engines which exist today from 100 h.p. to 7,000 h.p.

All propellers in the series should conform to a basic design policy so that the fundamental research and experience on vibration and functional problems should be capable of direct application throughout the complete range. The necessity for standardisation of the airline operators' tooling and test rigs also has a large influence on this policy.

The object of the next section of this paper is to show how this problem can be approached in practice.

BLADE DIAMETER AND ROOT SIZE

Figure 3 shows that propeller diameter varies approximately directly with $(SHP)^{\frac{1}{4}}$

so that, to a first approximation, a range of diameters varying in geometrical progression would be the most suitable.

From a study of the steady stresses set up in a propeller at the static condition where these are highest, it can be shown quite simply that constant steady stresses are obtained in geometrically similar propellers of varying sizes running at constant tip speed.

Now the strength of a propeller is largely determined by the critical diameter of the structure retaining the blade in the barrel. Therefore, one would expect the blade shank size to vary linearly and directly with basic blade diameter. A review of the various blade designs of Hamilton Standard and de Havilland propellers shows that the influence of other factors tend to confound this theory.

Figure 8 shows the variation of root diameter with blade diameter, together with a theoretical line based on the above reasoning. It will be seen that at the extremes of the diameter scale the practical curve shows larger shank diameters than the linear relation. At the low end of the scale this occurs because of the poorer vibration characteristics of engines with small numbers of cylinders, while at the higher end, it is caused by the appearance of aerodynamically excited vibrations in the propeller running range.

Thus we have an empirical curve associated with a given design of propeller which shows the limiting diameter which can be carried on a given shank size and which is substantiated by all the data which is available on steady and vibration stresses on that particular propeller design.

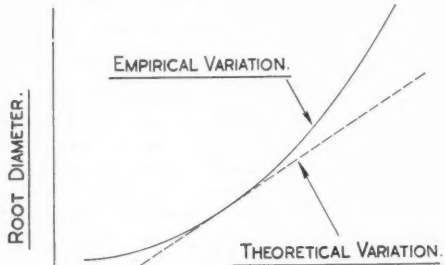

Fig. 8.
Relationship between blade and root diameters. Dural blades.

From experience it is found that a basic blade must be capable of being used down to about 75 per cent. of its limiting diameter. If it is used below this diameter the specific weight of the propeller becomes uneconomically high.

Thus the multiplying factor relating the diameters of basic blades in geometric progression must be greater than 0.75 if there are to be no gaps in the range of blade diameters available. In the de Havilland range this factor is actually about 0.87, giving basic diameters of 17, 15, 13 and 11.5 feet.

To carry these basic blades, hubs will be required to fit the basic root sizes corresponding to these diameters. Ideally, it may be best to have a series of both three and four-bladed hubs, but as the propeller becomes a more and more complicated mechanism, it seems more practicable to limit the propellers of the larger diameters to the four-bladed type.

8. STEADY STRESSES

The main stresses which are considered in a propeller are those directly caused by centrifugal force on the blades, bending moments on the blade as a cantilever caused by air thrust loads and the centrifugal twisting moment of the blade about its own axis of rotation.

The centrifugal twisting moment is proportional to the square of the rotational speed and its origin can be seen from Fig. 9. It is this twisting moment, combined with the friction of the thrust bearings resulting from the centrifugal force on the blades, that the pitch changing mechanism has to control.

For a typical 16 ft. diameter propeller the centrifugal load on each blade is approximately 60 tons and the centrifugal twisting moment may amount to 13,000 lb. in. for each blade at maximum take-off r.p.m.

The calculation of the bending moment is rather involved because of the existence of a restoring moment which is caused by the centrifugal force acting on the outboard sections of the blade, which are deflected because of the air thrust loads. The centrifugal forces on the blade and the air load bending moments are usually combined to establish the minimum areas and section

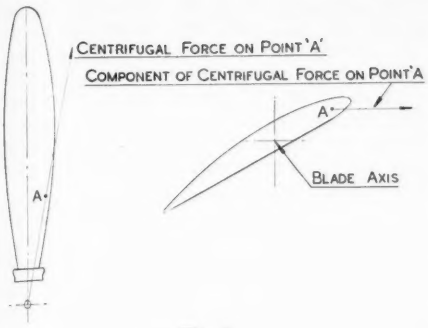

Fig. 9.
The origin of centrifugal twisting moment.

moduli throughout the blades, so that the stresses shall not exceed half the proof strength of the material.

Because of the nature of the steady forces acting on a propeller, their magnitude can be accurately determined and, if it were not for the presence of vibratory stresses, a considerable reduction in safety factor resulting in a large saving in weight could be achieved.

9. VIBRATION STRESSES

There is little doubt that if all propeller blades were stressed, due to steady loads, up to half the proof stress of the material, then failures would most definitely be experienced because of fatigue. By this it is meant that in a great many cases, it is the vibration stresses alone which will decide the scantlings of the blade and the main structural components of the propeller.

In the realms of vibration there is no substitute for experience and in the initial stages a laborious programme of trial and error is necessary to establish the permissible vibration stress limits for various components and the effect upon those limits of detail changes in the structure. It is the necessity of obtaining this background that makes it so important not to depart too far from a standard range of propellers embodying a sound basic design.

In general, vibration stresses are divided for investigation into two main categories:—

1. Those affecting the blade over that portion which is of aerofoil section.
2. The shank end and its retention in the propeller hub.

In the first of these categories the permissible vibration stress limit is dependent upon the result of fatigue tests upon blades eroded to a standard representative of prolonged service operation.

During strain gauge testing, stresses may be recorded which are above permissible limits, and either the blade modulus at the highly stressed section is increased by local thickening, or the whole blade stiffness is altered by progressively increasing or decreasing the moduli of sections along the blade. By this method the resonance can be shifted away from a condition at which the propeller will be required to operate.

In the second category the permissible vibration stress limits are also established as a result of full-scale fatigue tests. At this point in the structure however, there is usually no margin for increasing the modulus of the section once the propeller has been produced and considerable care is needed in the initial design investigation.

The natural frequency of the blade can still be altered by changes to the outboard section of the blade and in this manner resonances can be so shifted that operating stresses can be reduced to a certain extent. Large reduction in stresses cannot be achieved in this manner and the only remedy is the fitting of a larger propeller.

The use of vibration dampers to overcome excessive propeller vibration stresses should be treated with extreme caution, whether they be fitted in the propeller for the reduction of propeller stresses or in the engine primarily for the reduction of engine stresses. Recent experience suggests that it is possible with a damper operating erratically, to record stresses in the propeller which fluctuate to a greater extent than the safety factor employed would allow. In general, engines have a greater factor of safety with dampers inoperative than the propeller operating under the same conditions.

The only true measure of operating vibration stresses in a propeller is that recorded in flight on the correct aircraft installation under all conditions, including maximum and minimum take-off weights, and over the range of all normal speeds, powers and altitudes.

It can be shown that a strain gauge test on a propeller, made in an engine test hangar, will bear little resemblance to the final results in flight and can only be used as a rough preliminary check and, in some instances, explain the causes of unexpected failures during bench testing. In some cases the stresses recorded during strain gauge testing in a hangar can be far greater than

those experienced during all normal flight, because of turbulent air conditions peculiar to that particular test hangar.

The main reason for the necessity of strain gauge recording in flight is the rapidly increasing importance of aerodynamically excited vibration stresses; a secondary and less frequent reason is the shift of propeller resonant speeds caused by the change in propeller natural frequency with blade angle variation in flight.

Of the aerodynamically excited orders, by far the most important is that which is excited at a frequency of 1*P* (where *P* is the rotational speed of the propeller) caused by the air flow through the disc of a propeller in flight not being parallel to the axis of rotation.

It can be shown by simple propeller theory that the aerodynamic forces exciting this type of vibration are roughly proportional to the square of the indicated flight speed and the angle between the propeller thrust line and the air stream through the propeller disc.

This angle is principally affected by the attitude of the aircraft in flight, the nacelle position relative to the wings, and the distortion of the air flow caused by the influence of the fuselage and other bodies.

Since the incidence of the aircraft varies with wing loading at a given air speed, it will be recognised that in general this type of vibration becomes a more serious problem as wing loadings and speed ranges increase. The development of engines of increasing power requires propellers of large diameter and activity factor and these characteristics, with their adverse effect on the natural frequency of the propeller, still further increase the severity of the problem.

This type of aerodynamically excited vibration cannot be completely eliminated, and can only be reduced in severity by suitable choice of thrust line incidence and by designing propellers which are strong enough to keep the resulting stresses within permissible limits.

The structural design of a propeller is centred around the method of retaining the blade in the propeller hub. The object of all design studies on this problem must be to provide a fixing of minimum diameter which will fulfil the specification requirements of stiffness and load carrying capacity. It is the design of this feature which will determine, to a large extent, the specific weight of a propeller.

In all cases it is the vibration stresses which will determine the scantlings of the blade retention and, therefore, the primary object of the design must be to reduce the concentrations of stress to a minimum. Wherever possible the use of screw threads should be avoided, since even with careful detail design a very high stress concentration factor will result.

10. MATERIALS

For the propeller blade the range of materials is a wide one, comprising high density impregnated wood, magnesium alloy, aluminium alloy and steel. The main criteria for blade material are stiffness/weight ratio which should be high, ability to withstand fatigue stresses, high resistance to erosion from stones, gravel, sand and water spray and, to a somewhat lesser extent, ease of repair.

The main advantages of the impregnated wood blade are that it is light and a considerable degree of internal damping can be obtained, which reduces the general level of the vibration stresses. The lightness of the blade is sometimes offset by the weight of the steel fittings necessary to enable the blade to be retained in the propeller hub against the action of centrifugal force. Blades of this type are very susceptible to climatic conditions and extremes of heat and cold and of humidity can cause considerable problems.

Magnesium alloy must be rejected for its poor resistance to fatigue stresses in the presence of surface erosion, which cannot be controlled and is always present on the outboard sections of the blade.

Aluminium alloy is perhaps the most widely used blade material and can be said to fulfil all the design requirements up to a diameter of about 15 feet. Since the natural frequencies of blades fall with an increase in diameter, the need for keeping the resonance of fundamental modes outside the operating range makes it imperative to increase the stiffness/weight ratio in the larger diameters. This demands the development of a hollow blade in which the section modulus of the blade can be varied at will, without major change to the weight: it can be readily appreciated that in a solid blade, weight and section modulus vary proportionately to one another.

Steel as a material suitable for hollow blade manufacture has been chosen because of all materials it lends itself more readily to

fabrication, and its surface is more capable of withstanding abrasion because of its superior hardness.

Figure 10 illustrates the range of blade designs covered by steel and aluminium alloy blades. The higher line shows the practical limit of aluminium alloy while the lower line shows the lower limit for hollow steel blades. Within the band covered by the overlap hollow steel blades will always be lighter, but the use of aluminium alloy will still be a practical possibility.

In order to justify the extension of the curves to the smaller diameters and high activity factors, it can be shown that reducing the diameter of a basic design of blade by cropping off the tip, will, if tip speed is retained constant, always result in higher steady stresses and higher centrifugal twisting moments. This will mean that although the diameter of a given basic blade may be reduced to suit a given installation, the scantlings of the blade shank, propeller hub and pitch change mechanism will remain the same size as is required for the full diameter of the basic blade. Therefore, it is reasonable to assume that if, of two propellers at 17 ft. and 70 A F the steel-bladed propeller is lighter than that with aluminium alloy blades, then it will also be true of the same two propellers when reduced to 13 ft. diameter and 120 A F.

Within the band on the curve either type of propeller blade is still practicable and it is possible therefore to decide purely on a basis of the operating economics of the particular application, bearing in mind that high aircraft utilisation will be necessary to justify the higher prime cost of the steel blade. Outside this band little choice can be offered.

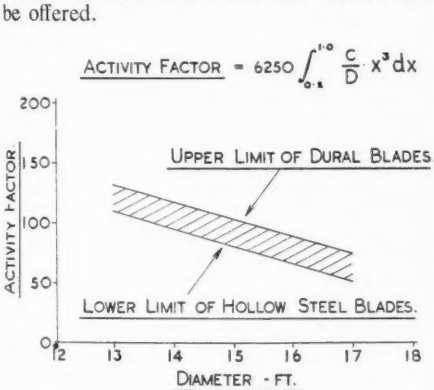

Fig. 10.

11. SPEED CONTROL

The speed range of the modern aeroplane has increased to such an extent in the past 15 years that some form of variable-pitch propeller has been accepted as essential.

In order to obtain the optimum performance from the engine, both in power and economy, it is essential that complete freedom to choose the operating conditions of the engine is maintained, irrespective of forward flight speed and altitude. It is therefore essential that an automatic means be provided for the control of blade pitch so that the engine speed is maintained constant at a preselected value.

12. FEATHERING

If the power plant for any reason fails to deliver useful thrust to the aeroplane, then it is synonymous to say that it will impose drag if the propeller is permitted to "windmill." It is necessary therefore upon these rare occasions to be able to change the pitch of the propeller blades to that which will cause the minimum drag and also, no tendency in the propeller to rotate the engine which may be damaged.

In the event of a fire in the power plant it is most important that all rotating components should be stopped before the normal fire extinguishing system is allowed to operate: for this reason the feathering and extinguisher system are interconnected on modern aircraft.

Feathering is accomplished by means of an auxiliary power supply quite independent of the normal control system of the propeller. This power supply can be energised either at the pilot's discretion or automatically upon some predetermined indication that all is not well with the power unit. A method is gaining favour whereby the propeller feathering system is operated if the torque from that particular engine falls below a minimum useful figure. A variation of this system is one in which the pilot has one emergency feathering control irrespective of the number of engines, and the torque meters on the engines are used to select that unit which is failing in power. This relieves the pilot of the necessity of deciding in an emergency which of his power plants is at fault, thereby saving many valuable seconds and sometimes avoiding the danger resulting from the feathering of the wrong propeller.

Rapid feathering is of extreme importance if the full advantage is to be gained from

this feature. Power plant fires, once started, can grow to alarming proportions in a very few seconds unless promptly dealt with; also, power plant failures during take-off and immediately afterwards demand that the drag of the propeller on the "dead" engine should be reduced as rapidly as possible.

The total time for the complete feathering operation must not exceed 10 seconds.

13. REVERSE PITCH CONTROL

The necessity for reversible pitch as one of the features of the modern propeller is rapidly becoming accepted. Its use should materially assist in combating tyre and brake lining wear; it will provide duplication in the event of failure of the aircraft wheel brake system and also, in an emergency on icy runways will provide the only effective means of stopping the aircraft.

The reversing propeller and the nose-wheel undercarriage are complementary to one another, each one tending to make the other more practicable: without a nose-wheel the aircraft is too unstable on the ground to make use of a reversible propeller and conversely, the nose-wheel type of layout puts a heavy strain upon the braking system of a modern aeroplane, which can be considerably relieved by a reversible pitch propeller.

There is also an increasing demand for reversible propellers as a convenient means of manœuvring flying boats against wind and tide, especially during the approach to moorings.

It has been demonstrated in America that this feature can also be used to accelerate the descent of an aeroplane from altitude while maintaining a low forward air speed: a very valuable contribution in the event of fire or pressure cabin blow-out at altitude.

It is generally considered necessary that the reversing propeller should be controlled by the pilot on the throttle: provision being made to move the throttles through a gate at the slow running position when further movement backwards would once again open up the engines: the movement of the throttle through the gate would initiate the necessary change of propeller blade pitch. This arrangement would then retain the same "sense" of correction should the aircraft tend to swing because of the uneven application of reverse thrust.

Normal operation would be to select "reverse pitch" by moving throttles through the gate at the slow running position immediately after touchdown. Considerable retarding effect can be produced without opening of the engine throttle and in any event full power would only be needed in an emergency.

Attention must be paid to the engine slow running characteristics when the propeller is in reverse pitch, since the air flow into the air intakes is quite abnormal and considerable difficulties can be experienced with engine "choking" when throttles are subsequently opened.

14. FUTURE PROPELLER TYPES

Ever since the introduction of the hydraulic constant speed propeller, the engine shaft oil transfer has been a definite limitation to the development of the propeller control system. In general, the engine shaft oil transfer has been developed up to a high standard of reliability, but it has always precluded the use of the higher pressures so necessary to produce the large operating forces required by the ever-increasing size of blades. Without these higher pressures, the size and weight of control mechanism has inevitably increased, and with them, the associated difficulties of sluggish operation caused by the large volume changes required for even small changes of propeller blade angle.

The necessity for the propeller to share the same oil system as the engine has been the source of a considerable number of operational failures, caused by the presence of foreign bodies and sludge in the oil. Engine oil, because of its relatively high viscosity, is also most unsuitable for use in low temperatures, at altitude, or in the Arctic when in the virtually stagnant condition in propeller pitch change mechanism.

The future trend in the design of the larger types of propeller will be towards a fully self-contained unit with its own self-contained oil supply, and complete freedom from rotating oil transfers. This type of propeller will end the age-long battle between engine and propeller designers for space to accommodate propeller ancillary equipment.

Conclusion

The authors would like to thank all those who have contributed directly and indirectly to the contents of this paper.

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DISCUSSION

A. V. Cleaver (The de Havilland Engine Co. Ltd., *Associate*): At the extreme speeds of modern aircraft the weight of the total power plant to produce a given thrust became the dominant factor. Even if they could get a propeller efficiency of 80 per cent. at over 500 miles an hour, that still would not make the propeller the best choice, because propeller thrust was inversely proportional to the flight speed. There had been a tendency in America to suggest that the propeller would still play a part at high speeds, but it would have to be confined to the low speed sphere in which, as the President had said, the propeller still had many years of useful life.

Was rotational tip speed or helical tip speed the better parameter of noise level? Could they regard noise as being purely associated with rotational tip speed, or was the forward speed component significant? The gas turbine, which liked to cruise at a high percentage of its maximum r.p.m., seemed to be a special case for the two-speed gear from the noise angle and also because the power-altitude characteristic of the engine was rather like an unsupercharged piston engine, with relatively high take-off power compared with that for cruising at altitude. The great difficulty of designing a two-speed airscrew reduction gear was known, particularly on turbines, and possibly it had been thought that the complexity of design was not justified, even for the suppression of noise and the improved performance.

Little was heard these days about the advantages of compressed wood blades. There were arguments about blade materials, but now it seemed to be almost entirely about different types of metal blade.

Probably the lecturers had not said much about the governor and pitch change mechanism on turbine propellers because the subject was in such an early stage.

The authors quoted a time for the feathering cycle; what rate of pitch change was now considered desirable for the reversing operation, since no time was quoted for that?

On the purely functional side of the propeller, the self-contained propeller was one of the biggest further contributions to be made. It would relieve the operators of a great many troubles caused by those foreign bodies which got into the propeller from the engine oil system, and it also had other advantages against freezing at altitude, etc. The advantages of such a system were so obvious that he wondered why it had been so long materialising.

C. O. Vernon (*Assoc. Fellow*): What was the author's opinion on the values of efficiency about which they had talked? They had said it was much more important to quote to aircraft designers' values of efficiency which were strictly comparable as between one propeller and another, rather than that the absolute values should be just right. He agreed it was essential they should know the effects of changes in the various parameters, but it would be nice to have the absolute values as well. He was interested in it from the point of fixing the aircraft drag. The only way in which it could be measured in flight now was to equate it to the thrust and measure that. They could measure the engine power by means of torque meters, but they did not yet measure thrust. They were told that even if they put thrust meters on they would not be any good because owing to the complicated propeller-body interferences they would not know how to interpret the results. Was that still the position, or was there any hope of being able to sort it all out so that they could measure the actual efficiency in flight?

He agreed with what the authors said about diameter, and the use of the biggest diameter possible. Nevertheless disc loading had successfully gone higher and higher over the past ten years and it was worth trying to find out why. He thought it was largely due

to wing loading going up and up; flaps had not kept pace and consequently take-off speeds had got higher and higher and the value of J in the critical régime had therefore gone up and it had not been so difficult to get reasonable efficiency with high disc loading as might have been supposed at one time. Nowadays, in fact, when they compared one propeller against another, for rapid estimates they did not bother with static thrust nor did they take Mr. Mullins' " 80 miles an hour." They took " 120 miles an hour "—something corresponding to the climb speed immediately after take-off, which was a far more critical condition than the ground run.

It was said that overshoes as a de-icing means would cause something like two to four per cent. loss in efficiency, and that it would be there all the time. He would like to ask airline operators how the economics of that worked out: was it better to incur that loss, or throw away the overshoes and avoid icing conditions, if that were practicable?

There seemed to be some reluctance to use reverse pitch for braking because of the trouble of sucking up stones and the resulting damage to propeller blades. Could the authors give any rough rules, giving maximum disc loading and ground clearance to which they could work to avoid that sort of thing?

The self-contained propeller would be a very good thing; when were they going to get it, and how much would it weigh?

G. W. Bubb (Rotol Ltd., *Assoc. Fellow*): From a material point of view steel was superior to anything else but steel demanded a hollow construction and this involved elaborate tooling for production, which was expensive.

As hollow steel blades only began to show a definite advantage in propellers of diameters above about 15 ft. the total value of propeller business in this range was not going to be large relative to the whole output. Naturally the position was being influenced by the adoption of jets for aircraft which normally used the smaller propellers.

The opinion of aircraft constructors would be welcome regarding the proportion of business which would be covered by the range of propellers which could utilise hollow steel blades, because if the total number of blades which could be sold were relatively small then it would be difficult to cover the cost of the tooling.

Because of the elaborate tooling needed for hollow steel blades it was not easy to change the blade design, and there was a temptation to take an existing design of blade for a new propeller application. That might not always be the most desirable design from the aerodynamic point of view. What was the lecturers' opinion?

The use of pre-selective feathering of the propeller to cut down windmill drag during an engine failure at take-off—as an automatic function—would appear to be an advantage by arranging a suitable button on which the pilot could keep his finger during the take-off operation and thus command automatic feathering. There was also a flight situation, which perhaps airline operators might say never arose, in which an aircraft was flying on the automatic pilot and there was no pilot at the controls. It would seem of advantage under such a condition to have a mechanical interlock on the button, which would, for the short time the pilot was not at the controls, also give the automatic feathering feature.

Considerable development work was being done on both systems, but the use of the automatic system had an added complication, that of providing for a momentary engine cut which brought in its train the necessity for some form of time delay element and the whole system became somewhat complicated. On automatic feathering it was not so essential to have the extremely high rates of pitch change that the pre-selective feathering system demanded.

W. N. Neat (de Havilland Engine Co. Ltd., *Assoc. Fellow*): The Germans had invented and tested the swept-back propeller blade and he saw from a recent magazine article that an American manufacturer had built one for wind tunnel and flight test. Had any results been obtained with that propeller and if so were they anything like the theoretical predictions?

Series 16, or similar sections, owed their effectiveness to the fact that laminar flow was preserved over the greater part of their contours. Did putting de-icing shoes to the leading edge of such blade sections seriously jeopardise their performance? Also, how critical was their performance to dimensional tolerances, and when a relatively high design lift coefficient was used in conjunction with a low thickness/chord ratio, might not the resulting concave face side introduce manufacturing complications?

An American manufacturer once claimed that square-tipped blades resulted in improved low speed and high speed performance. He conceded the former point, but it was inconceivable that high speed performance would be improved since the greater part of the blade loading was transferred to the most unfavourable part of the blade from Mach number considerations.

Would the lecturers comment on that and also whether the same tip speed on a square blade would give more or less noise than with one of more conventional plan form?

K. W. Speller (Handley Page Ltd., *Associate*): To what degree did the flutter problem affect propeller design? Was it as critical a factor with high tip speed propellers as it was with high speed aircraft? Had much investigation been done in this direction?

The authors had said that the loss in propeller efficiency due to the most severe conditions of icing was 13 or 14 per cent., but by fitting overshoes, the loss was only two to four per cent. Did that mean that the overshoes were 100 per cent. efficient and that the overall loss in propeller efficiency was due entirely to the fitting of overshoes, or did a certain amount of icing still take place?

How was propeller pitch change effected from say, fine to braking pitch without over-speeding occurring? Was it solely a matter of rate of pitch change, and if so, what would be the absolute minimum rate of pitch change required to ensure that over-speeding was not possible?

G. E. Preece (Rotol Ltd., *Graduate*): He agreed that with hollow steel blades it was preferable from the weight point of view to increase blade width rather than the number of blades, but he thought that the problem of fairing the wider blades into the spinner would be more difficult, particularly on gas turbine installations for which the spinners were usually much smaller than the propeller designer would like. What were the lecturers' opinions?

In the paper it had been stated that whereas for Clark Y sections the minimum thickness-chord ratio desirable was 6½ per cent. it was possible, and even advantageous, to use thinner sections if N.A.C.A. 16 series aerofoils were used. He questioned this statement in view of some recent American data N.A.C.A. T.N. 1546 which suggested that for Mach Nos. less than 0.75 the optimum thickness-chord ratio was as high as 9 per cent.

It appeared therefore that for aircraft with cruising speeds around 300 m.p.h. the main virtue of thinning down blades to thickness-chord ratios in the region of 6 per cent. was to reduce blade weight.

On the question of aerodynamically excited blade vibrations the first propeller order excitation associated with non-axial flow through the disc was undoubtedly causing concern. Higher orders might also cause trouble as, for example, on gas turbine installations where the propeller was operating just ahead of a non-annular air intake.

N. E. Rowe (British European Airways, *Fellow*): He was impressed by the emphasis placed on vibration problems and particularly that there was little difference expected between the weight of propellers of piston and turbine engines of the same power, since the reduction of engine vibration had not resulted in any reduction of the weight of the propeller as was expected, the vibration apparently being traceable to aerodynamic causes. That seemed to him to be an important factor in the further development of propellers, especially the steel ones, which, he understood, were to be of rectangular plan form with square tips.

One of the slides had shown that a diameter of propeller of about 14 ft. seemed to coincide with the minimum weight. Did that mean that the minimum vibration was expected at that diameter, and if so why?

Was the increased area that was used at the tip, particularly on military propellers, and which was expected, apparently, in the development of steel propellers, likely to lead to further vibration or worse vibration effects arising out of the aerodynamic effects, particularly the yaw?

Was there any variation in noise in relation to thickness or profile; was it constant with any given tip speed and was there any effect of the thickness-chord ratio; was it an effect of the total thickness of the propeller at that point?

Someone had asked if the reduction in efficiency from overshoes was worth while to the operator; he most certainly had to have the overshoes on because he might have to operate in icing conditions for some time while circulating over an airport. In that connection hollow blades might be of value because they could be de-iced by internally applied heat.

He had always understood that there was quite likely to be a tip loss of efficiency but

that did not seem to be borne out by the results quoted in various places for square-tipped propellers.

T. E. Godden (Rotol Ltd.): In America, he understood, they had done a lot of work on automatic synchronising. Had much been done in this country?

The authors had stated that the big disadvantage with the orthodox type of propeller was that high pressure transfers could not be used. He did not know if that were true; much work had been done on high pressure transfers but there was still plenty of chance for it to work and it could well be initiated on self-contained propellers to bring relative simplicity and reliability to this type of propeller.

N. J. Hancock (Ministry of Supply, *Assoc. Fellow*): He understood the lecturers to say that 12 in. clearance between propeller tip and fuselage was regarded as a reasonable safe distance to obviate noise in the cabin. What other factors affected that clearance? For example, what was the safe distance to avoid blade vibration, and what was the safe distance to avoid fuselage vibration? Were any figures available?

Were the fuselage proximity conditions truly simulated during the hangar tests, and if so at what clearance?

Dr. H. Roxbee Cox (President, *Fellow*): Like Mr. Vernon and Mr. Rowe he had been interested in de-icing overshoes. Clearly some method of de-icing airscrews was needed which did not reduce efficiency at all. Mr. Rowe's suggestion of hollow blades with internally applied heat was a possible method, but he thought that to get the heat there and pass it through the blades would be difficult. Had other methods been seriously considered? There was the possibility of introducing some very high frequency vibration into the blade which would have the effect of shaking off anything that tended to adhere. Probably this would not be a very popular idea—one generally tried to get rid of vibration, not to introduce it.

Vibration was the biggest difficulty in airscrew design. Could the lecturers say what, roughly, would be the difference in weight between a propeller designed with reference to vibration considerations and one which was not? In other words how much of the weight of the airscrews was there to deal with vibration? If that were known the maximum percentage it was possible to save by minimising vibration trouble would be known.

Was flutter serious? Did its prevention cost any weight? In some forms of airscrew he thought it safe to say it did not, but in metal airscrews with small thicknesses it probably had quite an effect on the total weight.

A speaker had commented that measurements he was employing had not hitherto been done, because no one could understand what the answers were when obtained. It seemed to him that as a principle it would be bad to measure for the sake of measurement. There were people who just collected data, went on collecting it, and at the end scarcely knew what to do with it. But sometimes it was a good thing to measure in a certain amount of ignorance. The chief duty of the scientist was to explain the things which happened, and he thought that in the present context it would be very good to obtain some thrust measurements. With data of the right kind it might be possible to make some further useful deductions not only about the amount of thrust delivered, but how it was finding its way into the general body of the aeroplane. They should take steps to measure thrust, not only of propellers on piston-engined aeroplanes, but the thrust which was delivered by jet propulsion engines.

It had been pointed out that because of the incidence effect on the blade disc they had a 1*P* order of frequency, while with two propellers going in opposite directions, one behind the other, they had a 5*P* to 10*P* order. Were these higher frequencies of any importance in design?

REPLY TO THE DISCUSSION

Mr. Cleaver: They had to confess that they had no exact data as to whether rotational or helical tip speed was the more important in determining the noise emission of propellers. From the results of the few tests which had been made covering a comparatively small range of speeds between 150 and 200 m.p.h., the rotational tip speed appeared to be the more important. Some theoretical papers of European origin had deduced that the noise from a propeller depended on a speed vector lying between the rotational and helical tip speeds.

For aeroplanes cruising at speeds up to about 400 m.p.h., rotational tip speed was probably a satisfactory parameter, since there were so many other factors such as the

geometry of the aeroplane, the degree of sound proofing and the altitude at which it was flying, which affected the problem to a greater extent than the errors which this assumption incurred.

On the rate of pitch change required for reversing propellers, the authors' opinion had been fairly stable over the past few years and they thought that for landing brake propellers 30 to 40° per second at maximum r.p.m. would be quite satisfactory. For air braking at high forward speeds of 300 to 400 m.p.h. calculation suggested that rates of pitch changes as high as 80 or 100° per second might be required.

Although the self-contained propeller had been looked upon, during the war years, as an ideal for which to aim, it had not seemed the correct decision to make such a radical change in design at that time when rapid production had been such an important consideration. Since 1945 the propeller industry had been changing from military to civil applications and like many other branches of the Aircraft Industry had found that this change was a larger one than had been imagined. Consequently with so many things to do, the self-contained propeller had not yet materialised in this country.

Mr. Vernon: In theory the absolute value of efficiency in flight could be measured by mounting a pitot rake in the propeller slipstream behind any parts of the aircraft which were in the slipstream. By this means it would be possible to measure the net thrust with the propeller running, and to measure the drag of the aircraft parts in the slipstream with the propeller removed. From these two sets of readings the propulsive thrust from the propeller could be deduced. In practice, the mounting of the pitot rake would be extremely difficult and the nearest approach to this had been to mount them close behind the propeller on a single-engined aircraft, and to measure the thrust from the propeller blades. Unfortunately, this technique explained nothing of the effect of the slipstream on the body drag which would probably remain a mystery.

The increase in propeller disc loading was, as Mr. Vernon suggested, almost entirely due to the increases in wing loading with the associated increases in take-off and cruising speeds. As speed increased the optimum disc loading tended to increase.

Little was known about the erosion of blades on braking propellers since little practicable experience had been obtained. There was no doubt that abrasion became worse as the ground clearance decreased.

The weight of the self-contained propeller should not be appreciably different from present-day propellers, if the reduction in engine weight accruing from the omission of drives for propeller equipment were balanced against the increase in propeller weight due to the self-contained feature. It was naturally difficult to predict a date for the availability of self-contained propellers, but production in three or four years did not seem unreasonable.

Mr. Bubb: It appeared true to say that the greater part of the cost of tooling for the steel blade was in basic equipment and not in those parts of the tools which were changed in the event of a new blade design. Considering the cost for the dies for the dural blades, there was no real reason why tooling charges need be so very much higher. The initial cost of the capital equipment was much higher, but that imposed no limits to a change of blade shape.

It was difficult to follow Mr. Bubb's reasons for suggesting that "automatic" feathering would not require such a high rate of feathering as was demanded by the "preselective" system, since in the case of engine failure at take-off it was always advantageous to complete the feathering operation as soon as possible after it had been decided, either automatically or by the pilot, that the engine really had failed.

Mr. Neat: Two years ago de Havilland Propellers Ltd. had manufactured a swept-back blade, but almost as soon as that work was completed research work on gas turbines increased so much that no facilities were available for propeller testing. This state of affairs still existed and no performance tests had been done on this propeller.

As Mr. Neat suggested, the effect of de-icing overshoes would be expected to be more severe on Series 16 aerofoils than on Clark Y sections, but the few tests on which data was available did not bear out this theory, and suggested that the loss due to overshoes was approximately the same on Clark Y and Series 16 blades.

The manufacture of propeller blades with concave faces was being accomplished satisfactorily.

With square tip blades the increase in aerodynamic loading at the tips did not seem

particularly detrimental to either the performance at high tip speeds or to noise level of the propeller. This was possibly due to a combination of very low thickness chord ratios and pressure leakage from the blade tip.

Mr. Speller: With metal-bladed propellers only stalled flutter was of consequence in design, and up to the present, although flutter had been detected audibly, subsequent vibration measurements had shown the resulting torsional stresses to be quite small.

The figures quoted in the paper for the loss of efficiency due to the de-icing overshoes assumed that there was no ice on the overshoes.

When the propeller blades were changed from the fine pitch position to the braking position the r.p.m. were kept within safe limits simply by using a high rate of pitch change and allowing the inertia of the system to prevent the r.p.m. rising. No absolute minimum rate of pitch change could be specified, since it depended on a variety of conditions.

Mr. Preece: It was quite possible that the introduction of hollow steel blades might increase the difficulty of fairing blades successfully into the spinner surface, but that depended a great deal on the particular design of steel blade considered.

Mr. Preece's statement that some American data had suggested an optimum thickness-chord ratio as high as 9 per cent., was only true if low design lift coefficient were considered. For the lift coefficients at present used for propeller blades there was a definite advantage in reducing thickness chord with N.A.C.A. Series 16 sections.

Mr. Rowe: It was quite true on piston engines that propellers of about 14 ft. diameter appeared to suffer less from vibration than those of smaller or larger diameters, since the smaller diameters were generally associated with engines having a small number of cylinders and consequently, somewhat poorer vibration characteristics. At diameters of 15 ft. and 16 ft. the blade natural frequencies had fallen far enough to make aerodynamically excited vibration a more critical condition than it was at about 14 ft. diameter.

The use of wide tips on a hollow steel propeller blade certainly aggravated many vibration problems, but the propeller weight increase necessary to combat these difficulties was smaller than the increase in weight incurred by increasing blade area by any other means.

No test work had been done to investigate the effect of secondary variables such as thickness and thickness-chord ratio on the noise from propellers.

Mr. Godden: A certain amount of test work on synchronisation of propellers was proceeding in Great Britain, but rather more experience had been gained in the United States.

Mr. Hancock: Although 12 in. had been suggested as a reasonable tip-fuselage clearance from the aspect of propeller noise, it was a very approximate figure and while a similar distance could be suggested from the vibration point of view, the effect of other variables such as fuselage construction was large. For example, although several aircraft were flying quite successfully with clearances as low as 5 in., trouble had been experienced on other installations at clearances of nearly three times this figure.

Dr. Roxbee Cox: The amount of weight built into a propeller to deal with vibration stresses was something that could not be measured, but they felt that a figure of about 30 per cent. would give a reasonable measure of its importance.

Even with very thin metal blades difficulties because of flutter in propellers were not expected. Although the 1*P* propeller stresses were becoming important in the larger sizes, frequencies of much higher orders were present, generally due to engine excitation, and sometimes these could be of considerable consequence.

FATIGUE OF AIRCRAFT STRUCTURES

by

P. B. WALKER, M.A., Ph.D., F.R.Ae.S.

The 776th Lecture was read before the Society on the 31st March 1949 at the Institution of Civil Engineers, Great George Street, London, S.W.1. Dr. H. Roxbee Cox, B.Sc., D.I.C., F.R.Ae.S., F.I.Ae.S., President of the Society, introduced the lecturer, Dr. P. B. Walker, M.A., F.R.Ae.S., Head of the Structures Department at the Royal Aircraft Establishment.

INTRODUCTION

At the present time there are indications that structural fatigue may become a major factor in design, at least for some types of aircraft. If this be so the prospect is disturbing to the aircraft designer. There are already the two criteria by which structural efficiency is judged—static strength and stiffness—and if one more of comparable significance is to be added, namely fatigue strength, the complication is serious.

Apart from being a complication, fatigue inherently presents the designer with several major difficulties. When the metallurgist and the physicist have finished with fatigue, the designer's task has scarcely begun, and he has a further problem in the behaviour of a complex structure, both in relating that behaviour to fundamental theory of fatigue and in relating it to the external loading conditions encountered by the aircraft.

The situation is rendered much more difficult by lack of knowledge of the basic nature of fatigue, which metallurgists and physicists have not yet been able to supply. Thus the designer is faced with the task of creating a complex structure out of basic material and elements the behaviour of which is imperfectly understood.

An important effect of this lack of fundamental knowledge, and of the complexity of the purely structural aspects of fatigue, is that emphasis is thrown on testing and experimental work generally. Here again the designer is faced with a major difficulty. Fatigue testing of large structures takes considerable time and is extremely costly and a comprehensive study of fatigue properties by this means, merely for the purpose of developing one particular design, is generally impracticable. The difficulties of time and cost may be reduced by testing parts of the structure separately, but they are still appreciable and, what is more important, the tests are inconclusive as regards the behaviour of the same components when acting as part of the larger structural unit.

In the light of these preliminary considerations fatigue is seen as presenting a serious problem in aircraft design, and as requiring study from the design standpoint over and above what it may also require as a fundamental scientific problem. The present paper has been prepared with this predominantly in mind. It is intended to be a review of the whole subject of fatigue from the standpoint of the aircraft designer.

There is also included a brief account of those general principles which have been established by past experience. In this respect there is no conflict with the main objective of the review, since an understanding of such principles is essential to an appreciation of the aircraft designer's problem.

1. THE BACKGROUND OF FATIGUE

1.1. Definition

The first thing that is required in any discussion of fatigue is a good working definition of what it is supposed to be. The word "fatigue" refers generally to a rather vague phenomenon and its precise meaning is liable to change with advancing knowledge. There is a tendency, moreover, for it to be interpreted differently by the various kinds of specialists. It might have a different significance, for example, to a metallurgist concerned with basic material properties than to a structural engineer who sees a broader picture.

For the purpose of the present review it is necessary to have a definition as comprehensive as possible. It is therefore proposed to define fatigue as comprehending all the

effects of repeated or fluctuating loading which impair structural properties, but which are not ordinarily produced by a single application of load.

There are some aircraft engineers who speak of "repeated loading of aircraft structures" in preference to "fatigue of aircraft structures," with a view to overcoming any doubt which might arise as to the meaning of "fatigue." This practice implies some fundamental distinction between fatigue of aircraft structures and fatigue of other kinds of structures which there is no evidence to justify. The word "fatigue" is established in the engineer's vocabulary, and although some flexibility in interpretation may be desirable, it is too late to discard it altogether.

1.2. "Classical" fatigue

When aircraft engineers first became seriously concerned with fatigue there was already available a wealth of knowledge acquired in other branches of engineering. For half a century engineers of various kinds had studied the subject intensively. Railway engineering provides a good example, for not only were locomotives and rolling stock subjected to fluctuating loads, but so also were the rails and bridges over which they passed. Other types of engineering also had their own particular fatigue problems, which not only led to an accumulation of empirical knowledge, but also provided an incentive for fundamental scientific research.

The first task of the aircraft engineer, therefore, is to decide how the already existing knowledge and experience of fatigue, acquired in other branches of engineering, can be put to best use. To ignore it altogether is clearly wrong, and would delay progress by many years. On the other hand, there is much that is irrelevant in the earlier work, and many of the working rules evolved are, from the aircraft standpoint, definitely misleading. To quote one important example, the conception of an "endurance limit," by which a structure might resist indefinitely the repeated loading imposed upon it, affected the entire outlook of structural engineers in the early days, but at the present time it has no place at all in aircraft engineering.

1.3. The modern aircraft problem

The situation thus calls for the subject of aircraft fatigue to be treated essentially as an extension of the general subject of fatigue but, as is yet to be shown, covering a range of conditions that are entirely new. Before these new conditions are discussed it is desirable to examine more closely what is comprehended by the subject of aircraft fatigue. When fatigue was first considered for aircraft it implied little more than the application of existing practice established in other branches of engineering. Attention was given mainly to a few particular components liable to fluctuating loads produced by the engine or by vibration generally.

The modern problem of fatigue is a comparatively recent development. It is characterised by being much more comprehensive. In the first place, fluctuations in the entire load system are considered. In the second place, the effects are examined for the entire structure. Recognition of this wider significance of aircraft fatigue represented a change of outlook attributable primarily to two causes. First there was the coming into general use of light alloy as the principal material for aircraft construction. Secondly, there was the deeper realisation of the effects of gusts and air turbulence generally as agencies producing considerable variation of applied load.

The conditions which distinguish the aircraft fatigue problem from the general one are several. First, there are the imposed load fluctuations which, on any reasonable basis of comparison, are more severe for aircraft than those ordinarily encountered by most other structures. Secondly, there is the widespread use of light alloy with its inferior fatigue resisting properties compared with steel, on which most of the earlier work on fatigue is based. Thirdly, there are a number of effects arising from the attempt to obtain structures of extreme lightness, of which the use of light alloy is but one. This concern with weight economy has led in various ways to improvement in static strength and stiffness but not infrequently at the expense of resistance to fatigue. The use of thin sections and numerous rivets is an example of this trend, while the precise study of structural theory has permitted working at higher stress levels in resisting static loads, without necessarily obtaining corresponding justification in relation to fatigue.

All these adverse effects are counterbalanced by the fact that a much shorter working life is required from aircraft than is expected from most other structures. The differences between the modern aircraft

fatigue problem and the earlier problems encountered in other branches of structural engineering, in fact, may be summed up by this marked difference in required working life. The aircraft engineer has to deal with the situation as he finds it, and efficiency demands that he take the realistic view in providing for the life required, and in not attempting to make his structure last indefinitely.

1.4. Characteristics of Fatigue

There are a few characteristics of fatigue which the aircraft engineer can accept as established by earlier investigators. The first contradicts all the implications which the word "fatigue" brings to mind. Fatigue in general is not analogous to tiredness or associated with powers of recovery. It is essentially a process of destruction, and ordinarily a piece of material undergoing repeated loading is approaching ultimate failure.

There are exceptions to this general rule about recovery. Certain steels may recover from the effects of load variations within a limited range of stress, provided that periods of rest are allowed. So far there is no evidence of light alloys possessing this property, while it is doubtful whether, even if powers of recovery comparable with the steels mentioned did exist, the aircraft designer could afford to work within the narrow limits of stress required.

There is a possibility, moreover, of recovery being effected by artificial means as distinct from mere resting. Some steels show a marked response to a slight raising of temperature. Methods of producing recovery from fatigue for light alloys do not exist at present. The point is of interest, however, from the standpoint of the future since, if convenient methods of annealing an aircraft structure *in situ* were evolved, the fatigue problem for aircraft would be greatly simplified.

Another characteristic of fatigue is that there are practically no external indications that it exists until actual failure occurs. Even microscopic examination of sectioned specimens reveals little until failure is almost imminent. This characteristic of fatigue greatly increases the danger from fatigue failure. It also provides an incentive to the aircraft engineer to ensure, if possible, by structural means, that should fatigue failure occur its effects are not immediately catastrophic.

1.5. Fundamental Theory

While certain characteristics of fatigue are known, there is unfortunately no satisfactory theory to explain the basic phenomenon. Fatigue has been tentatively explained as a result of hysteresis, with a departure from strict elasticity too small to detect in a single loading and unloading process. There is nothing which enables the behaviour of materials in fatigue to be ascertained without test and little, if anything, which helps the structural engineer in carrying out his particular task.

In the absence of a precise theory of fatigue, emphasis has naturally fallen on data acquired by tests. There has been evolved, moreover, an empirical "working theory" of fatigue which has been used extensively. The main purpose of this empirical theory is to enable the best use to be made of data obtained by tests and, conversely, to reduce the amount of testing which need be done, by taking into account well-established general trends. It was developed mainly for the steel structures met in ordinary engineering, but is applicable in some degree to aircraft structures, from which standpoint it is presented and discussed in this review.

2. PRESENTATION OF TEST DATA

2.1. Endurance Curves

The empirical approach to the fatigue problem has led to certain conventions in the presentation of data obtained by experiments. Most of the fatigue tests take the simple form of a loading cycle repeated until the specimen breaks. It is not proposed to enter into details of how such tests are made. Literature on this subject is comprehensive and no particular benefits are to be expected from a condensed review of methods which are constantly being improved, but it is worth-while to review the general character of the results of such tests.

It is proposed to consider in the first instance only tests done on polished bars of material subjected to direct stress. This ensures reasonable consistency in the figures obtained for various conditions. At the same time it should be remarked that, although the results are different, the method of presentation is applicable to more complicated specimens such as structural elements and complete structures, which are discussed later in more general terms.

Test data is usually presented in the first instance in the form of " endurance curves " which indicate the number of times a specified load cycle must be applied to produce failure. Each endurance curve relates to a series of different forms of loading cycle conforming to some general pattern, so that each individual one of the series may be defined by a single parameter, usually a " load " that is characteristic of the cycle. For the purpose of general discussion this load is conveniently expressed as a fraction of the static ultimate, *i.e.* of the load required to produce failure in a single application. The number of applications is usually plotted logarithmically.

Endurance curves are sometimes known as S/N curves, S denoting stress and N the number of applications. Such notation can only be used for simple specimens, however, for which stress is readily definable. For general structural work it is more convenient to speak of load and to refer to the curves as " endurance curves." Further discussion of endurance curves is best related to specific cases.

2.2. Simple repeated loading

Figure 1 gives a curve obtained from a series of simple repeated loading tests. Any particular point on this curve corresponds to a single experiment in which a polished bar made of light alloy is repeatedly loaded and unloaded in tension until failure occurs. Initially the specimen is unloaded (see inset Fig. 1), and a force is progressively applied until it reaches some specified value (P_o). The force is then progressively removed until the specimen returns to its original unloaded condition, and the completed cycle is repeated as many times as is necessary to produce failure.

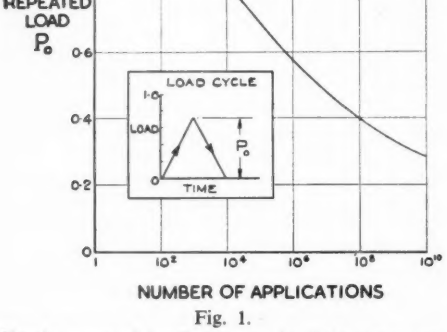

Fig. 1.

Simple repeated loading curve for light alloy bar.

For a small number of load applications the method of counting comes up for question. Do we count the greatest number of applications which the specimen can withstand without failure, or the number required to produce failure? Furthermore, since we speak of repeated loading, do we refer to the number of applications or the number of repetitions? The issue can be settled by considering the case of direct static loading to destruction. The convention is that, whatever numerical system is used, the vertical axis denotes the static loading condition, so that in the simple repeated loading case the curve cuts the vertical axis at unity. As to whether the vertical axis is labelled " zero " or " one " is a matter of choice, but whatever is intended is indicated by the horizontal scale. Use is made of this freedom in plotting curves to avoid inconvenient scales of figures. Thus for direct plotting the vertical axis corresponding to static loading is usually labelled " zero," and for logarithmic plotting it is usually labelled " one."

As to the form of this particular curve, it is to be noted that, working up the logarithmic scale, the load falls off slowly at first, then rapidly, and finally slowly again. In the example shown the curve is still falling at the extreme limit of 10^{10} applications. This is typical of light alloy specimens, and marks a contrast with the majority of steels for which the curves tend to run horizontally at this stage. The flattening out of the curve for steel corresponds to the " endurance limit " for steel specimens which, at the appropriate stress level, can be loaded an indefinite number of times without producing failure. There is no evidence to indicate that an endurance limit of this kind exists at all for light alloys.

2.3. Simple reversal

The foregoing general characteristics of the endurance curve for simple repeated loading mostly obtain also for other modes of loading which can be represented by a single variable. There is one such other curve of particular importance—the simple reversal curve. For this, an initially unloaded structure has a load (A_o) progressively applied and then removed as before (see inset Fig. 2). The same load is then applied in the opposite sense, after which the

specimen returns to the original condition of zero loading, the complete process forming one loading cycle. Any point on the main curve of Fig. 2 corresponds to repeated application of this cycle until failure occurs.

Mention has to be made of the convention of expressing load as a fraction of the static ultimate, since there are now two static ultimates to be considered, one for compression as well as one for tension. In a case like this the tension ultimate would be chosen if the two were different, so that the actual loads applied in reverse direction would be the same. In a general treatment of the subject it is usual to assume not only equal static ultimates, but also symmetric properties generally in tension and compression. This procedure simplifies the general study of fatigue properties without affecting basic principles or broad conclusion. In specific cases the procedure adopted is a matter of discretion.

In Fig. 2 the previous repeated loading curve is also drawn for comparison with the reversals curve. It is seen that the two curves start from the same point, corresponding to static ultimate, on the vertical axis. As the number of applications increases the load for the reversals curve falls well below the repeated loading curve.

At this stage the danger must be emphasised, in this particular field of work, of allowing arbitrarily chosen methods of presenting data to influence conclusions. It might be argued with some justification that the two curves intersect at unity on the vertical axis because they have been made to do so. If full range of variation of load had been plotted instead of maximum values, the reversals curve would show twice the range of the repeated loading curve at the vertical axis, and the two curves would then converge until they almost coincided for a high number of cycles.

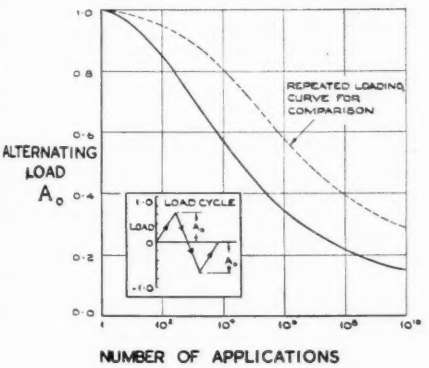

Fig. 2.
Simple reversal curve for light alloy bar.

There is unfortunately no standard practice for representing reversals of load, some workers on fatigue preferring range and others preferring alternating load, which is half the range. For the aircraft engineer it is generally more convenient to use the alternating load so that the two simple curves for repeated load and pure reversal start off from the same point corresponding to static loading, and this practice is conformed to throughout this review. It is of interest to remark, however, that workers in steel, concerned primarily with comparison at the endurance limit at the other end of the scale, might well prefer the other system.

2.4. General endurance curves

The simple repeated loading curve and the simple reversal curve may each form the basis for a much wider range of loading conditions. The repeated loading curve may be generalised by raising or lowering the minimum from zero. Fig. 3 shows a number of curves drawn for various values of the minimum. Similar generalisation is possible for the reversals curve by raising the mean from zero. Fig. 4 shows a series of curves for various values of the mean about which the load reciprocates. Both diagrams relate to a mean loading that is positive, *i.e.* corresponding to tension. For material with symmetric properties the same curves can be used for a mean value corresponding to compression, by simply replacing tension by compression and vice-versa.

It is of interest to remark that both systems separately cover the entire field for loading between any two extremes. As to which is used is a matter of personal choice. Many workers in fatigue consider both, in order to recognise more readily general trends in the fatigue properties which are sometimes best revealed by one and sometimes by the other. There is a tendency, however, for one or the other to be regarded as fundamental. Thus some workers regard the general loading case with two variables as an extension of the simple repeated loading case and others as an extension of the reversals case.

The main point at this stage is the number of curves which, by either system, are required to cover the whole field. To establish any one curve requires a series of experiments that take considerable time to make, the task being aggravated by scatter of results through variation in nominally identical specimens. To cover the entire field experimentally, therefore, is an almost impossible task. It is to meet this situation that the empirical theory, next to be described, has been evolved. The objective is to enable the complete series of endurance curves to be derived by calculation from a few particular ones that can be obtained in complete form by experiment.

3. THE EMPIRICAL THEORY

3.1. Loading parameters

The empirical theory is mainly concerned with the relationships between three variables. One of these is the number of cycles required to produce failure. The other two variables define the loading cycle. To avoid confusion with load generally as a variable within a cycle, it is proposed to refer to them as "loading parameters."

Pairs of loading parameters may be selected in various ways to serve special purposes. Two particular systems are selected as having the widest scope for general application.

The first system of loading parameters (see Fig. 5) defines the extremes of loading and we may use the following notation,

P = maximum load;

Q = minimum load;

where maximum and minimum are interpreted in their usual algebraic sense.

The second system defines the maximum fluctuation of load about a mean or steady value, and we may use the notation,

A = Alternating load or semi-range;

M = Mean or steady load.

The two systems are then related by the formulæ

$$A = \tfrac{1}{2}(P - Q);$$

$$M = \tfrac{1}{2}(P + Q).$$

As previously mentioned some workers in fatigue use the range (R) instead of alternating load (A) where

$$R = 2A = P - Q.$$

Although it is not proposed to use R in this review it is sometimes convenient to refer to the alternating load as the semi-range.

3.2. Constant endurance

The endurance curves previously described (Figs. 1-4) are examples of the use of this notation and of its underlying principles. Thus the "repeated loading" family of curves (Fig. 3) shows the relation between maximum load (P) and endurance N, for particular values of (Q) which are constant for any one curve. The "reversals" family of curves (Fig. 4) requires the alternative notation and shows the relation between alternating load (A) and endurance (N) for particular values of the mean load (M).

The empirical theory is based on a different approach. The relationship is sought between the two chosen loading parameters when the endurance or number of cycles to

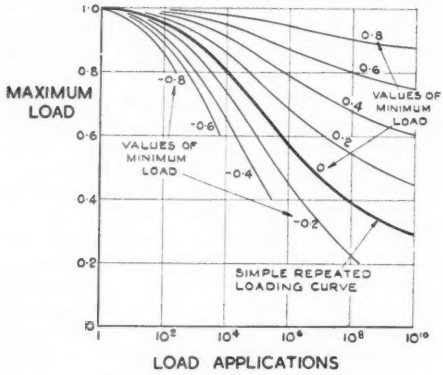

Fig. 3.

Generalisation of repeated loading curve for range of minima.

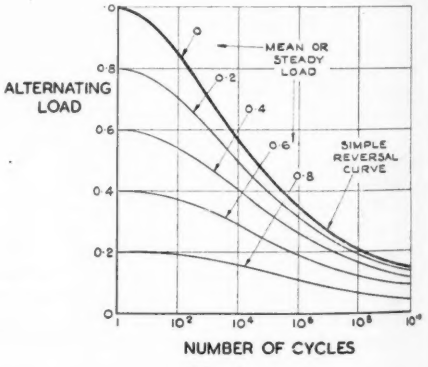

Fig. 4.

Generalisation of reversal curve for range of mean loadings.

destruction is kept fixed. Thus the objective becomes to produce what may be termed "lines of constant endurance."

It is important to note at this stage that this method of treatment of the three main variables could not be used initially for the direct presentation of experimental data. It is characteristic of fatigue testing that endurance is the one variable which cannot be determined in advance. A test has to be made for set conditions of loading and the endurance is not known until the test is completed. General theoretical study is not bound by such practical limitations.

At first sight the method of constant endurance might appear little more than a system of cross-plotting, but the relationship between the loading parameters corresponding to the same endurance reveal general trends that may be subjected to semi-theoretical treatment, and the extent of variation is limited by over-riding considerations that are to be described.

3.3. The Master Diagram

The substance of the empirical theory may be incorporated in a single diagram (Fig. 6). The immediate objective is to draw curves showing the relation between alternating and mean load for particular values of endurance. The horizontal axis AB is used for mean load (M), expressed as a fraction of the static ultimate. The vertical axis AC is used for alternating load (A), also expressed as a fraction of the static ultimate.

The first step is to ascertain the limitations on the variation of A and M imposed by the condition that the static ultimate cannot be exceeded. For the line BC, indicated in the diagram as "the barrier of the ultimate," it is seen that

$$P = A + M = 1$$

so that any point on this line corresponds to a maximum load equal to the static ultimate, and hence the line cannot be crossed. Since in the first instance attention is being confined to positive values of the mean, and since alternating load (A) has no sign and can therefore be treated as positive, the entire field of variation has thus been reduced to the triangle ABC.

The next process avoids having to identify any line of constant endurance by specific numbers of cycles and ensures that the diagram may have a general application. It is assumed that a simple reversals endurance curve is in existence giving the relationship between alternating load (Ao) and number of cycles for zero mean load. Any given number of cycles, although unspecified numerically, may thus be indicated by the corresponding value of the alternating load (Ao) on this curve. We can therefore mark, at convenient intervals, points on the vertical axis through which the lines of constant endurance we intend to draw shall pass. The appropriate endurance for each line will then be indicated by the particular values of alternating load represented by these points.

There exists one further piece of general information to be made use of still. The point B referred to as the "focal-point" in the diagram (Fig. 6), corresponds to a mean load equal to the static ultimate, so that the alternating load A is in the limit zero. Hence all the lines of constant endurance must pass through it. Thus the task is

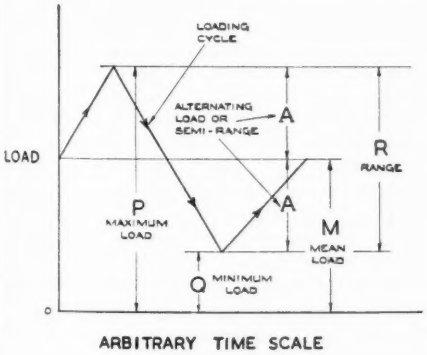

Fig. 5.
Key to notation.

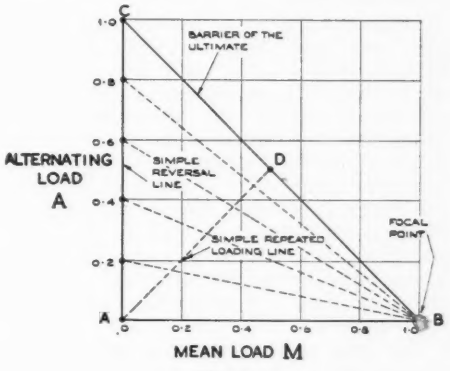

Fig. 6.
Construction of the master diagram.

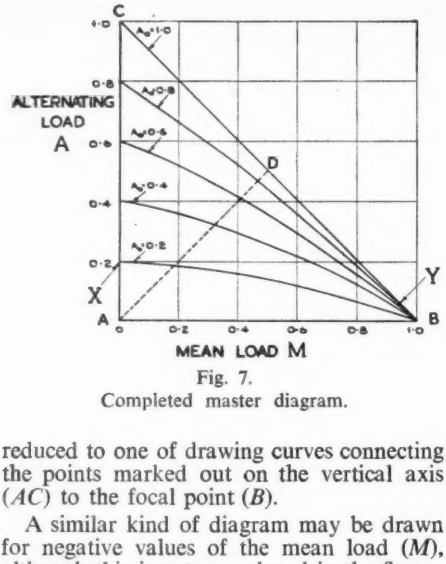

Fig. 7.
Completed master diagram.

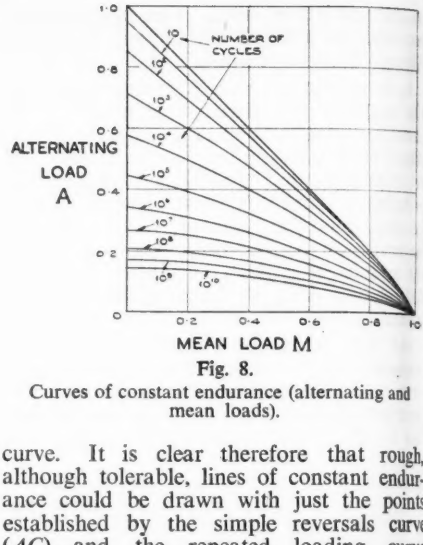

Fig. 8.
Curves of constant endurance (alternating and mean loads).

reduced to one of drawing curves connecting the points marked out on the vertical axis (AC) to the focal point (B).

A similar kind of diagram may be drawn for negative values of the mean load (M), although this is not reproduced in the figure.

3.4. Classical curves

Many proposals have been made for formulæ defining these connecting curves. The one known as the "modified Goodman" gives straight lines, and has the merit of simplicity. Another, by Gerber, gives parabolas with axes running downwards along the vertical co-ordinate axis (AC). Gerber curves show a fair degree of accuracy over a limited working range for steel, but the higher curves cross the ultimate barrier; and it has to be assumed that, after intersection, the barrier line is followed instead of the parabola.

In general the earlier workers in this field were concerned mainly with the endurance limit at which loading cycles can be applied an indefinitely large number of times. For aircraft structures, on the other hand, practically the entire range has to be covered. It therefore seems desirable to regard this empirical approach as a means of establishing merely the general shape of the curves of constant endurance. In other words, the objective is to enable all the endurance curves to be derived from a carefully selected few that can be obtained directly by experiment.

The line AD in the diagram (Fig. 6) corresponds to $A=M$, or, in other words, it represents the repeated loading endurance curve. It is clear therefore that rough, although tolerable, lines of constant endurance could be drawn with just the points established by the simple reversals curve (AC) and the repeated loading curve (AD). Greater accuracy than this may be necessary in particular cases, and more endurance curves obtained by experiment will then be required.

3.5. Further considerations

In the search for a general indication of the shape of curves of constant endurance there are three further rules which might give guidance.

First, if there is to be reasonable continuity in the entire field the curves should form a family which degenerates into a straight line as the ultimate barrier is approached.

Secondly, experience indicates that, for reasonably low values of the mean load and alternating load, or in other words, when the maximum load is much less than the static ultimate, the response to a given alternating load is insensitive to variation of the mean load. Thus at point X in Fig. 7 the slope of the curve is very near horizontal.

Thirdly, for the upper curves in the region marked Y in Fig. 7, there are reasons to suppose that the effect of the maximum being near the ultimate tends to over-ride the effects of small load fluctuations, so that the upper curves tend to cling to the line BC.

The validity of all these three arguments is open to question, but they indicate a general trend for which there is appreciable experimental support, namely that the curves

in general are convex upwards and lie above the straight lines of the modified Goodman formula.

The curves shown in Fig. 7 have been specially produced with some regard to these rules, and are a family of parabolas with continuous variation, and include as special cases the terminal straight lines *AB* and *BC*.

It is interesting that these curves, and most other curves that have been suggested, show a discontinuity of slope as the mean load *M* changes from positive to negative. The Gerber parabolas avoid this but, as already stated, introduce a discontinuity for the higher curves as the static ultimate is approached. There seems to be no way in which virtual discontinuity in slope can be avoided for the higher curves somewhere in the field. It does not follow, moreover, that there are any general rules as to where it should be that are applicable to all materials.

3.6. Derived curves

Since the master diagram covers all the degrees of possible variations of endurance and the two loading parameters, the various forms of curve required to suit particular purposes can be obtained by cross-plotting, provided that there is one endurance curve to indicate the true scale of numbers of cycles. All the endurance curves shown (Figs. 2 to 4) have been derived in this way from the assumed repeated loading curve of Fig. 1.

Likewise, the lines of constant endurance can be plotted in terms of numbers of cycles, as would normally be done in dealing with particular structural specimens. Fig. 8 shows Fig. 7 when transposed in this way. It is also possible to transpose into terms of upper and lower limits of load, as shown in Fig. 9. In this last diagram curves are stopped at conditions corresponding to zero mean load so that *P* is always numerically greater than *Q*.

4. THE FATIGUE BEHAVIOUR OF STRUCTURES

It is now proposed to consider the behaviour of complete structures. For these the methods already described for the treatment of experimental data still apply, with possibly certain reservations. The actual results obtained, however, may differ considerably from what might be expected from consideration of material properties alone. In the fatigue behaviour of structures there are several effects which are not present when material is made up in simple form.

4.1. Riveted joint

Before dealing with a complete structure it is convenient to consider first typical structural elements. In this way certain of the structural effects may be discussed apart from the further complications which arise when the elements are connected together to form a complete structure.

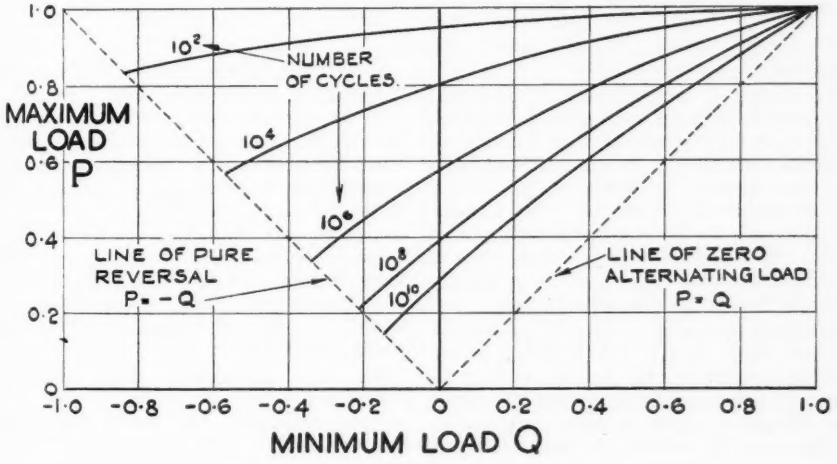

Fig. 9.
Curves of constant endurance (maximum and minimum loading).

One of the more interesting structural elements from the fatigue standpoint is the riveted joint. Fig. 10 shows a typical repeated load curve for a riveted joint, with a corresponding curve for a polished bar of the same material.

It is seen that, when the load in each case is expressed as a fraction of the appropriate static ultimate, the failing load for the riveted joint falls rapidly away from that of a polished bar. For any appreciable number of cycles, therefore, the riveted joint is much weaker than would be expected solely from a knowledge of its static strength and of its material properties.

The main explanation is to be found in two causes:—

(*a*) The presence of local stress concentrations;
(*b*) The effects of early permanent deformation.

These two causes are closely related, since a stress concentration may give rise to permanent deformation, while permanent deformation may, in fact, relieve a stress concentration.

With regard to the stress concentration, there is evidence which establishes that this in itself is a primary cause of impaired fatigue resistance, but in general the direct loss of fatigue strength is less than would be expected from the magnitude of the concentrated stress alone. A stress concentration corresponding to a local stress equal to four times the average in the immediate neighbourhood, for example, might give a fatigue strength about half what there would be if no stress concentration were present at all.

The effects of local permanent deformation are rather more complicated. Local distortion is an essential part of the process by which rivets efficiently transfer load from one main member to another. In a direct loading test of a riveted joint the transfer of stress tends to be uneven at first and to produce comparatively high local stresses As load increases relief is progressively obtained through flow of the material.

The effect of this on static strength is that a higher value is attained than would be expected from the behaviour of the joint in its earlier stages of loading. On the other hand, fatigue strength in general relates to a lower level of loading, so that there are higher stresses than are necessary because of bad distribution of load.

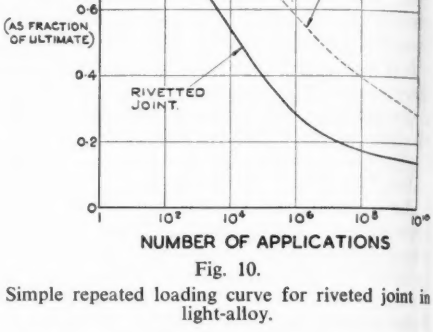

Fig. 10.

Simple repeated loading curve for riveted joint in light-alloy.

There are further complications arising from local permanent deformation. In the first place the effects on basic fatigue properties of material are not fully understood. For simple specimens the effect, whatever it may be, is confined to the higher load levels, say above three-quarters of the ultimate. In the riveted joint, permanent deformation may be present in some degree for any loading cycle worth investigating.

In the second place, the fatigue behaviour of a riveted joint may be greatly influenced by previous history. Thus a single application of a severe load might improve subsequent loading distribution, and thereby improve the fatigue properties also.

4.2. Structural elements in general

Other kinds of structural element may also show fatigue properties inferior to those that might be deduced from consideration of material properties alone. The main explanation in most cases is the presence of stress concentrations. These may be brought about by such things as abrupt changes of section, holes, sharp corners and surface irregularities. These characteristics may be detrimental to static strength also, but usually the loss of fatigue strength is much more pronounced.

In this connection there should be mentioned the conditions under which simple specimens are tested for material properties. The object of such testing is to obtain properties which are specific to the material. Even in such simple tests care

has to be taken to ensure that variations are not introduced that do not depend upon the material. Scratches and any other surface irregularities, for example, impair fatigue properties, and hence the insistence on a high polish. The need for having basic data that is consistent, and strictly comparative as between one material and another, justifies these precautions, but it has to be borne in mind that even simple pieces of material as used on a real structure will not approach the standard of finish of material test specimens.

Among other factors affecting fatigue strength are initial stresses such as may occur in castings, forgings and rolled sheets. For these an applied fluctuating stress may be superimposed on a different mean stress from what the external loading system would appear to indicate.

There are also the effects of non-linearity of the stress-strain relationship present at low loading levels. Examples are to be found in initial slack in rivets, pins and bolts, complicated by the effects of friction. Another example is the panting of sheets and the formation of tension fields. In a static test to destruction most of these, as well as other similar effects, either completely disappear or are secondary, but they may assume considerable importance in respect of fatigue at low loading.

4.3. Complete structures

The behaviour of a complete structure naturally depends upon the behaviour of its constituent elements, but there are further complications now to be considered.

The most important complication is the changed significance of ultimate static strength when used in reference to a structure. It may well be argued that static strength has nothing to do with fatigue, and that fatigue should be considered on its own merits. Aircraft engineers, however, are liable to be seriously handicapped without some such simple standard by which to judge fatigue strength. This being so, the fact has to be faced that the part which fails in a static test is not necessarily the part which fails in fatigue. The static strength of the structure as a whole, therefore, is no true indication of the static strength of a part which fails in fatigue.

This difficulty may lead to misinterpretation of a fatigue test made on a complete structure. A tailplane, for example, might be supported at the root by bolts in tension and fail in a fatigue test at some point further outboard. A hasty conclusion might then be drawn that bolts in tension are satisfactory from the fatigue standpoint, whereas the likely explanation is that the bolts in this particular case were two or three times stronger than necessary to carry the static load.

A somewhat similar effect might arise through variations in the comparative vulnerability of different parts of the structure in different parts of the fatigue range. Of two particular components subjected to the same fluctuating loading, one may fail first for one loading cycle, and the other fail first for another loading cycle. The complete endurance curve may thus consist of a number of parts corresponding to fatigue failure of quite different structural components.

4.4. Internal load distribution

Futher complications arise on a complete structure through erratic behaviour of the internal load distribution. When a simple test specimen is subjected to fluctuating load in direct tension or compression there is an almost exact correlation between applied force and internal stress. For the complete structure there is no such simple correlation. Even for static loading conditions the determination of internal loads is extremely difficult for a modern aircraft structure. When the external loads fluctuate determination of internal response may become for all practical purposes impossible.

At lower loadings the normal load distribution may be disturbed in many different ways. All the various factors already mentioned as affecting the fatigue behaviour of structural elements may have this effect. Thus pre-stressing of material, and non-linearity of stress-strain relationship, may not only affect the fatigue response of individual elements to given loads, but may actually change the loads applied to them. It is possible also that developing fatigue may affect internal load distribution, although there appears to be insufficient evidence to arrive at a conclusion about this.

Even more pronounced effects may be expected at the higher loadings which give rise to widespread permanent deformation. As is the case with a purely static loading condition, this may lead to a drastic change in the internal load distribution, complicated by

the fluctuations in the externally applied loads. The result is that on most modern aircraft structures the fatigue behaviour beyond the elastic limit of loading is scarcely amenable to rational analysis.

The re-distribution of load with the general onset of permanent deformation also exercises, although indirectly, an effect on fatigue properties over the entire loading range. This effect is entirely attributable to the practice already mentioned of expressing fatigue strength in terms of ultimate static strength. The ultimate static strength benefits considerably from the re-distribution of load through plastic deformation, but in general this is entirely absent in the lower ranges of fatigue loadings which usually are the main objective of study.

4.5. The hidden fatigue danger

The foregoing remarks concerning internal load distribution apply to a well-balanced design in which the onset of plastic deformation takes place roughly simultaneously over the entire design. In addition to the effects so far considered, an extremely serious loss of fatigue strength may arise when one particular component in the process of static loading reaches its proof loading well in advance of the structure as a whole, and then obtains relief from further loading by its extension. Under fluctuating loading conditions such a component may be loaded to a much higher proportion of its ultimate strength than the rest of the structure.

Ordinarily such weakness might be condemned as bad design, even from the standpoint of static loading, since a minimum external loading condition is usually prescribed for which no part of the structure must exceed its elastic limit. Failure to meet this requirement, however, is not always discernible on test. Furthermore, the local plastic extension is most likely to occur where static strength can easily be overlooked, or where it can only be assessed with difficulty. Thus the part affected may be a small bracket or a piece of skin not intended to carry primary load, but for which the effects of failure can be serious. Alternatively, it may be a part overloaded through some unforeseen concentration of load such as occurs near large holes and structural discontinuities.

These various considerations all point to one conclusion: that the fatigue characteristics of a complete structure can only be ascertained with certainty by testing it in complete form. The need to do this does not lessen the value of test data obtained from material specimens and structural elements. On the contrary, such data is clearly necessary to make the complete test worthwhile, since the testing of complete structures is a wasteful process if used to discover weaknesses in components that could have been detected by simpler means.

5. THE EXTERNAL LOADING ACTIONS

From the consideration just given to the behaviour of a structure it is seen that the structural engineer has a task which extends beyond the region covered by specialists in fatigue of materials. For the aircraft designer there is a still further extension in which account is taken of the complexity of the external loading system and of its variation under realistic operational conditions.

5.1. Complex load systems

The first problem to be encountered arises from the complexity of the external forces. The forces on an aircraft are usually large in number and act in various directions. There is thus a possibility of these forces varying in some measure independently of each other, so as to make general consideration difficult.

For the present purpose it is proposed to assume that, for any particular case, proportionality of external loads is maintained and severity of loading can be represented by a single load factor. Thus the fatigue loading cases, as in the simpler tests already described, have a single variable defining load, with two parameters, such as the upper and lower limits, defining any particular loading cycle. The justification for taking this course lies first in the fact that the aircraft engineer, no less than the materials specialist, must proceed in stages, and there are problems to be solved which are of greater urgency than the one being circumvented. Secondly, the fluctuating forces encountered by an aircraft, at least in the more important cases, do tend to conform to this principle. It is common practice to take for granted that variation of the entire loading system is represented by variation of a single load factor. The possibility of the assumption being wrong, or at least inaccurate, however, must always be borne in mind.

5.2. Cumulative effect of mixed cycles

The second problem arises from the complex laws of variation of loading which arise even when, in a particular case, the complete system of forces can be represented by a single variable. The forces on an aircraft in flight fluctuate in what appears to be an indiscriminate manner, and there may be no suggestion of anything approaching the regular loading cycles used in ordinary fatigue tests.

It is convenient to approach indiscriminate load fluctuations in stages. The simplest case for investigation is a mixture of different loading cycles instead of a continuous repetition of a single one. It is convenient to consider first cycles which lie on the same endurance curve as represented in Fig. 11. A number of cycles are applied corresponding to a point A on the curve, but before enough (N_1) have been applied to produce destruction, loading proceeds corresponding to another point B, and so on.

To deal with this problem a cumulative rule has been suggested. The underlying physical principle of this rule is that in relation to fatigue a material has a definite characteristic which may be described as "vitality." This vitality is consumed at various rates for different cycles, irrespective of what has happened to the material previously. Thus n applications of a cycle, requiring N applications to produce failure, consumes n/N of the total vitality; and the remainder is available for consumption at other cycles. The condition for failure is thus represented by the equation:

$$\frac{n_1}{N_2}+\frac{n_2}{N_2}+\text{——}+\frac{n_r}{N_r}=1$$

Unfortunately, the validity of this rule is much in doubt. There is evidence to suggest that it may hold with reasonable accuracy for a limited range of cycles. On the other hand, it is unlikely that it holds for a wide range of cycles as represented by the extreme ends of the curve in Fig. 11. There are reasons to believe, in fact, that the application of loading cycles of low intensity actually increases the fatigue resistance to severe loading instead of reducing it, a direct contradiction of the cumulative rule.

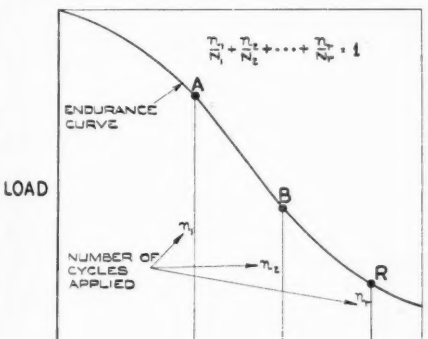

Fig. 11.
Diagram illustrating the cumulative rule.

5.3. Indiscriminate variation

The next stage of generalisation introduces cycles lying on various endurance curves such as are shown in the generalised diagrams (Figs. 3 and 4). This increases the variety of load cycles which have to be covered by any cumulative rule, but there is a further effect to be considered.

A single endurance curve has only one of the two parameters varying, the other being common to all the cycles. It is thus possible to pass from one cycle to another without a break, but when both parameters are varying, as in this more general case, there is in general no common point of transfer from one cycle to another. Hence there has to be an extension of the loading cycles or a curtailment.

The effect is unlikely to be serious if the number of changes is small compared to the number of cycles of each kind applied. With many such changes not only is the particular cumulative rule mentioned likely to be wrong, but the possibility of the laws of behaviour being covered by any simple cumulative rule is in question.

From this last condition it is but a short step to the indiscriminate loading sequence encountered on aircraft generally in the course of flight. The conception of cycles has now to be abandoned entirely, and replaced by increases and decreases of load in alternating succession.

In the absence of precise knowledge of the fundamental character of fatigue, the only way of establishing how well a structure will stand up to fluctuating loads is to apply a loading sequence representative of actual

conditions. Given this sequence the experiment is practical, although there may be some mechanical difficulties. The real difficulty is to find the representative loading sequence.

5.4. Loading data

To the aircraft designer the external loading actions on an aircraft are just as important as the fatigue effects in response to given loads. Considerable effort is expended, nowadays, in determining the fluctuating loads on an aircraft, and there is no shortage of information of this kind. What is required is a typical cross section of what occurs in the course of a long period of flight. The mere quantity of data may operate against the achievement of the desired objective, since it may prevent analysis being made in any acceptable period of time. The problem of obtaining operational data from fluctuating loads on aircraft that is really useful is receiving considerable attention at the present time.

In this connection there is a possible line of development which appears worth pursuing without detracting from the effort given to direct measurement of fluctuating loads. The underlying principle is to seek some apparatus which, while responding to external loading, carries out some measure of interpretation from the fatigue standpoint. In fact it may be possible to measure indirectly the rate at which the fatigue life of the aircraft is being used up.

For this purpose there might be considered a piece of material or small structural element carried on the aircraft and loaded in a corresponding way. The apparatus might conceivably take, for example, the form of a weight suspended on a cantilever. Care would have to be taken, however, to provide suitable damping and natural frequency. A simpler alternative would be a piece of material connected to the structure in such a way as to pick up load through strain.

The main purpose of the apparatus, in whatever form it were to take, would be to indicate by actual failure of a specimen piece of material or small structural element that the life of the aircraft was nearing its termination. The principle, however, could be extended to give advance warnings by employment of a series of elements of various fatigue strengths.

6. FATIGUE AND AIRCRAFT DESIGN

6.1. Principal factors in design

It is now proposed to consider the direct repercussions fatigue has upon aircraft design. The principal factors affecting design are:—

(*a*) The fatigue characteristics of the structure.

(*b*) The fluctuating loads the aircraft will encounter.

(*c*) The expected working life of the aircraft.

The first two have already been discussed, but the last raises further issues for consideration before the fatigue picture can be regarded as in any sense complete.

The three factors affecting design are presented in this way in order to emphasise their comparable importance. It is not easy to maintain a true perspective on these matters affecting design. Fatigue effects present a scientific problem of interest to a much wider circle of specialists than does the study of the fluctuating loads occurring on actual aircraft. From the designer's standpoint the correct determination of applied load fluctuations is just as important as knowing what fatigue effects are produced by any given loading conditions.

In general, moreover, considerations of the working life of an aircraft are equally important, although they are almost exclusively the concern of the designer. The working life of an aircraft is limited by considerations of obsolescence, wear-and-tear and the general economics of aircraft operation. Disregard of this limitation on life would lead to a serious loss of efficiency. It is in fact doubtful whether the entire conception of a modern aircraft could exist if its structure were expected to have a life comparable with that of a steel bridge or a building.

6.2. The designer's objective

With these principal factors in mind, and especially the limitations on structural life which exist independently of fatigue, it is desirable to attempt to set out precisely what the designer's objectives should be.

The simplest and most direct objective is to ensure that, without appreciable structure weight penalty, fatigue failure will not occur before the aircraft is removed from service in the ordinary way.

To this statement there are two corollaries. If the objective is achieved with certainty, with such margins of safety as may be necessary, it is not essential either to determine what the fatigue life is or to seek to increase it. Further investigation of the fatigue characteristics of his aircraft may be of interest to the designer, but it is not incumbent on him to undertake it.

Should this primary objective be for any reason unattainable, and consideration of fatigue have to determine the permissible life of the aircraft, then the designer has the more difficult task of deciding precisely what that life is. A reduced life for reasons of fatigue is not necessarily unacceptable. Although economic considerations are important, the greatest emphasis rests on exactness in the assessment of the fatigue danger so that the first knowledge of it is not revealed by an accident.

It may be that an extended fatigue life would be wanted, even at the cost of structure weight or with other penalties. In such an event the further task of the designer is twofold. He has to find the best way of increasing the fatigue strength, and to assess the penalties incurred in doing so.

6.3. Other considerations

There are one or two further points of detail which need to be taken into consideration in the interpretation of the main objectives.

The first involves recognition and appropriate regard to the fact that fatigue failure is not necessarily catastrophic. Although fatigue failure takes place without direct warning, it may be local and a modern aircraft structure may still hold together long enough for the weakness to be discovered and repair effected.

One effect on design of the existence of this non-catastrophic kind of failure is that the relative emphasis on design of different components of an aircraft will vary. Thus it is natural and reasonable to be most conservative in the design of a component the failure of which would clearly be immediately catastrophic.

There is scope for the designer, moreover, to anticipate the effects of local fatigue failure and to prevent its extension. This consideration applies particularly to cracks, which tend to extend. The designer can assist further by making adequate provision for regular inspection of the structure at critical places, without which the benefits of the warning given may be lost.

The risks of fatigue failure may also be reduced by arranging to exchange certain parts. Such a method may be acceptable for a new design if the designer can state precisely at what intervals the exchanges should be made, and facilitate the procedure by giving special attention in design. This method has probably its most useful application, however, in extending the fatigue life of an aircraft that already exists.

6.4. Assessment of the fatigue danger

It is appropriate to consider next how serious the fatigue problem has become and how serious it is likely to be in the near future. On such a subject it is not possible to speak with any degree of certainty. There are differences of opinion regarding even the present situation; but it is possible to set out certain facts and to give tentative views which might throw some light on the situation.

First, it is clearly a fact that many aircraft types have come and gone without experiencing fatigue failure, although it is important to note that these are not necessarily representative of present-day aircraft, to say nothing of future ones. More significant are the known records of fatigue failure. In general, the number of fatigue failures that have occurred is much less than is generally supposed. Furthermore, a large proportion of these appear to have been non-catastrophic and to have been revealed on inspection.

Lest this statement lead to undue complacency it is well to bear in mind that serious epidemics of trouble have developed in aviation from a few isolated incidents. Flutter is an example, and if the first warnings of danger from flutter had been disregarded, the consequences would have been extremely serious.

Apart from such general considerations, there are specific trends which give rise to concern for the future. The first is a tendency to require a longer working life from an aircraft, for which there are a number of reasons. First, it is a general rule that as progress is made rate of progress declines, and hence obsolescence becomes less effective in curtailing the prescribed working life of an aircraft. Secondly, improvements in design from the standpoint of robustness, and improvements in methods

of maintenance, are likewise extending the limit of life imposed by considerations of wear-and-tear. Finally, the tendency for increased initial cost of aircraft may, on economic grounds, operate in favour of retaining particular aircraft in service for a longer time.

The second reason for increased concern about fatigue in the future arises from the general tendency for aircraft to operate under more exacting conditions. Improvements in navigation and in methods of aircraft operation render practicable flying with less regard to adverse weather. In any given number of flying hours an aircraft may be expected to encounter a larger number of severe guests.

Finally, there are grounds for concern in the design trends which are being produced by the attempts to obtain more efficient structures by present-day standards, that is structures which are still lighter for a given static strength and stiffness. Primary load is increasingly being diffused over thin sheets or transmitted to components (stringers, stiffeners and the like) with thin sections, the whole being connected together by innumerable rivets. Thus the effect of working in material (light alloy) with inferior fatigue properties is being aggravated by the introduction of more stress concentrations.

6.5. Effect on design trends

It is clear that if fatigue becomes a matter of serious concern in the future the designer's task will be rendered much more difficult. Instead of having to consider two factors in design—namely static strength and stiffness—he will have three. The effects on general design trends are largely a matter for speculation and, in any case, must depend on how serious the fatigue problem becomes.

One effect may be that some designers at least will question whether steel was not abandoned prematurely in favour of light alloy. In any case there will be an incentive to discover materials with properties more like steel, even at some sacrifice of the lightness of light alloy.

Another effect may be a reversal of the design trends of recent years back towards earlier types of construction. Thus the extreme application of what may be described as the monocoque principle may have to be modified in favour of earlier methods with massive spars and more robust components generally.

An incentive may also be created for the investigation of glueing metal to metal as a substitute for riveting. Progress has already been made in the development of a metal to metal glue, but it is too early to assess its prospects of universal acceptance.

In considering prospective design trends regard must be paid to the fundamental research that is proceeding all the time. A radically new situation would be created, for example, by discovery of material with better fatigue properties, or by discovery of an easy method of annealing structures *in situ*. Furthermore, the development of a satisfactory theory to account for the basic phenomenon of fatigue might throw new light on the whole problem.

Acknowledgments

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DISCUSSION

H. B. Howard (Ministry of Supply, *Fellow*): On the pure materials research side they wanted to know more about the fundamentals of fatigue. In addition, there was the problem of the "cumulative damage" rule, which was being used to some extent by the designing firms. Sometimes it rather frightened people, and they were calculating very short fatigue lives. He thought that was probably wrong; but certainly they needed to know more.

The general tendency in tackling the problem seemed to boil down to the necessity to accumulate data about both gust loads and the existing strength of aircraft. Not much was known about how strong aircraft

were in fatigue, much less about how strong they should be. When they had established how strong aircraft were in fatigue and had built up a picture of the gust frequency, the two could be compared in order to determine at which stress level failure was most likely to occur. There was some evidence that that level was somewhat high; but more work was needed to establish some kind of standard test which all could use. One of the minor difficulties of the problem was that tests were made under different load conditions. Standards should be established on a sound evidential basis.

Possibly a tell-tale device of some kind coud be evolved; if they could carry on the aircraft a small specimen whose fatigue life was known to be less than that of the aircraft, it would be quite useful.

H. H. Gardner (Vickers-Armstrongs Ltd., *Fellow*): What should the designer do to ensure that fatigue troubles did not occur? What life was to be expected? Obviously they could not apply to aircraft the same factors as they applied to bridges; but they must find out the sort of life for which they must design. What tests could be applied to find out what life was to be expected?

A great deal of research had been done during the past few years, and nearly all the evidence obtained—by rather crude methods—had indicated that the probability of fatigue trouble on transport aircraft was rather greater than present experience indicated. That might be due to the technique applied; but, from a comparison of some of the actual results with the unit working stresses in the aircraft, the evidence was definitely gloomy.

In the paper the author had shown an S/N curve for a riveted joint compared with that for a polished bar. It was suggested in the text that the actual fatigue strength due to a possible stress concentration of four would be roughly half the endurance limit of the polished bar specimen. Tests on the polished bars for the alternating type of load had shown better results than the curves indicated; one series of tests showed the limit, at 10^7, was about $\frac{1}{3}$ of the ultimate. Some other tests which had been made, but which had perhaps not been continued for a sufficient number of cycles, suggested that even that result was pessimistic. When testing a simple stress concentration due to a plain hole in a polished bar, the stress reduction was a half; in other words, it was just as much as in the riveted joint case. Applying a stress concentration by means of a loaded hole, indicated as four, suggested that the maximum stress to which they could work was about a quarter of the ultimate. Translating that into figures, they obtained, for a 30/32 tons/sq. in. alloy, 10 tons as the fatigue limit at round about 10^7; that was halved by a simple hole, and halved again, to a quarter of the ultimate, for a stress concentration which might normally be expected. That meant that a stress of about 2.5 tons/sq. in. would produce failure in specimens after a number of reversals of the order of 10^7, which he considered to be rather a low figure.

That sort of picture was worrying designers; there was a good deal to explain in regard to the translation of test results, the technique of testing and interpretation for design purposes.

As to the life that should be expected, there were roughly 8,750 hours in a year. The operators suggested that they must operate their aircraft for at least five years, and that the aircraft should be actually flying during a fair proportion of the total hours in each year; so that a probable estimate for the life of an aircraft was 10,000 - 15,000 hours. They knew that, during the war, bombers had flown for not much more than 1,000 hours. Civil aircraft had exceeded that length of life; but fatigue troubles began to creep in after 2,000 hours, and there was a real danger that at between 2,000 and 10,000 hours troubles would arise. It might be only incipient trouble which could be observed and which could be overcome by changing components; but if in a fleet of aircraft it were necessary to change a whole host of components at about one-third of the life of the aircraft, the process could be very expensive.

The tests to be applied to structural parts to determine their endurance limits were very different from those to be applied to bars, etc. They had not yet a satisfactory method of testing pieces of structure to indicate their life; and he agreed with the author and Mr. Howard about the use of trial specimens. He believed the Americans were experimenting by sticking "coupons" on to structures, and that the work was yielding results, but there was much yet to be done even in finding out what sort of "coupon" would predict best the life of an aircraft.

There was more in the fatigue problem than they had at first believed, and there was

a great deal of research to be done to establish satisfactory design principles on which predictions of structural life could be based.

Dr. D. Williams (Structures Department, Royal Aircraft Establishment, *Assoc. Fellow*): The author had shown that the problem of determining the fatigue life of so complicated a structure as an aeroplane was one of frightening difficulty.

When they also considered how much had still to be learned about the frequency of different loads in flight, the situation from the aircraft designer's point of view was far from reassuring. The designer was at a loss to know what was expected of him. He wanted immediate advice on what to do while the long-term job involved in the gathering of data and in the general study of the fatigue problem was going on.

From that point of view two important facts were worth noting. First, fatigue failure due to loads greater than 50 per cent. of the ultimate static failing load was highly unlikely because of their relative infrequency in flight. In other words, the greater frequency of the smaller loads more than made up for their size. The real danger to aircraft from a fatigue standpoint came from gusts up to a strength of $\frac{1}{2}g$ or thereabouts.

An immediate and useful conclusion could be drawn from that fact. Let them imagine a fighter, a bomber, and a large civil aircraft traversing the same route; they would meet the same gusts and would be subjected to much the same g accelerations. A few high g manœuvres by the fighter and a few violent evasive actions by the bomber would have practically no effect on their fatigue lives, which therefore depended only on the gusts they met. But when they remembered that the same $\frac{1}{2}g$ gust subjected the large civil aircraft to 1/6 of its ultimate static load, the bomber to 1/10 of its ultimate static load and the fighter to only 1/25 of its ultimate static load, the handicap of the big civil aircraft was obvious.

The large civil aircraft had to cope with extra dynamic loads, due to wing flexibility, largely absent from the bomber and non-existent in the fighter, and in any case the lives of the fighters and bombers were necessarily short; thus it was easy to conclude that, so far as fatigue was concerned, they could largely disregard the fighter and bomber class of aircraft and concentrate attention on civil aircraft, particularly large ones.

That was a useful narrowing down of the problem.

The second important fact was that, when different specimens of the same component were fatigue tested under the dangerously small loads referred to, their endurances showed a wide scatter. They expected, in other words, that specimens of the same component having a mean life of 10,000 hours could depart from that mean by some thousands of hours. That was not only well known to metallurgists, but had been proved at the Royal Aircraft Establishment on built-up structures such as tailplanes.

That profoundly affected the designer's attitude to the fatigue problem, for the one thing he dreaded was a catastrophic fatigue failure. If he could be assured that regular inspection could give due warning of any such failure, he would be much happier, and could regard complacently each new aircraft he built as just another fatigue test specimen in a long-term investigation.

The necessary condition for that comparatively comfortable state of affairs was that all important loads should be shared more or less equally between as large a number of equal elements as possible. Fortunately that was just the condition that was being brought about by present trends in design. Heavy spars were disappearing, with their accompanying heavy joints, and the main loads in wings, fuselages, and tailplanes were being increasingly catered for by a multiplicity of stringers, with main joints consisting of a corresponding multiplicity of bolts.

The big scatter—amounting to thousands of flight hours—between the lives of individual elements ensured that inspection every 50 hours could not fail to spot incipient damage.

Cracks in the skin were easily seen, but a stringer could break clean through without immediately betraying the fact. Extensive stringer damage, however, could not take place without showing the fact by cracks in the adjacent skin, as tests had already indicated.

It might be objected that if one stringer failed, the others were not likely to be in a healthy condition, and a heavy gust load might suddenly break the lot. Luckily, that could not occur, for they had now a fair amount of evidence to show that static strength was little, if at all, affected by previous fatigue history.

A more valid objection was that even a skin stringer wing with no spar flanges usually had shear webs, and those could not easily be inspected, although failure could be serious. That might be met by making the leading and trailing edges alone capable of standing a moderately heavy load such as a 1g gust load, should the internal web or webs give way. At the same time, some facilities for inspecting internal webs must be provided, and the practice of putting lightening holes in such webs must be avoided at all costs, for they had been shown to be peculiarly liable to start cracks.

If a designer were committed to use heavy individual spar joints, he could not rely with any confidence on inspection to spot incipient cracks, but might use an American idea of criss-crossing very fine wire over the joint shellaced to, but insulated from, the surface, the breaking of a small steady current running through the wire indicating an incipient crack, and therefore approaching trouble. One felt that the best thing, however, was to eschew heavy spars, together with their joints.

As the dangerous fatigue loads were the result of gust encounters, a really efficient gust eliminator would go far to eliminate the fatigue bogy.

F. H. Pollicutt (Bristol Aeroplane Co. Ltd., *Fellow*): At Bristol they had made some investigations on the structural detail of their civil types. Their results, in a practical way, emphasised a number of Dr. Walker's points and indicated the extremely serious position into which their present lack of knowledge could lead them. The position was such that extreme pessimism now might eventually mean the premature rejection of a structural design that was statically most efficient and economically sound; and extreme optimism now might give aircraft having a life as short as two years or so.

Most of the investigations at Bristol had been directed to a typical Z-sectioned extrusion which they used throughout the main structure as longitudinal skin stiffening. The loading represented a vibration of, for example, the wing in flexure, giving a steady axial tensile stress with fluctuating stress of variable amplitude.

The testing machine used was the Avery-Schenck Pulsator, and testing began with the determination of the S/N curve for a typical Z-sectioned extrusion, in aluminium alloy to D.T.D. 364. The flanges were 1.2 in. wide, the web 2.3 in. deep, and the thickness 0.16 in. That result was extremely disappointing, at 10^6 reversals the fluctuating stress being only 20 per cent. of that published for D.T.D. 364 polished bar. Several changes were made in the method of fabricating the section and to the method of testing. Unfortunately a change in the type of testing machine was not possible.

The results were plotted in Fig. A. The numbers identifying the curves referred to the following sequence:—

1. Extruded Z-section stiffener of D.T.D. 364 material without rivet holes, loaded through fitting wedge grips. Mean stress 13,300 p.s.i.
2. As for 1, but with a typical row of holes drilled in one flange. Points were given for mean stress of 13,300 p.s.i. and 20,000 p.s.i.
3. As for 2, but with thrust races fitted to the grip assemblies so as to minimise torsion in the specimen. Mean stress 20,000 p.s.i.
4. Z-section stiffener geometrically identical with 1, machined from the fine grain portion of extruded D.T.D. 364 bar, held in wedge grips as for 1. Mean stress 13,300 p.s.i.
5. Z-section stiffener machined from the fine grain portion of extruded D.T.D. 364 bar with the same test section as 1, but with integral, headed ends. Minimum stress 2,000 p.s.i.
6. Extruded Z-section stiffener of D.T.D. 364 material with flanges removed over the central portion and ends held in wedge grips as for 1. Mean stress 13,300 p.s.i.
7. Polished bar specimens machined from fine grain extruded D.T.D. 364 bar material. These tests were made to compare the performance of four testing machines and to show the degree of scatter. Minimum stress 2,000 p.s.i.
8. Flat strip specimens cut from D.T.D. 646 sheet material, and having their edges polished. Minimum stress 2,000 p.s.i.
9. Riveted joint specimens geometrically similar to those of Hartmann, in D.T.D. 610 material, polished to reduce the depth of initial scratches. Minimum stress in line of rivets 2,000 p.s.i.

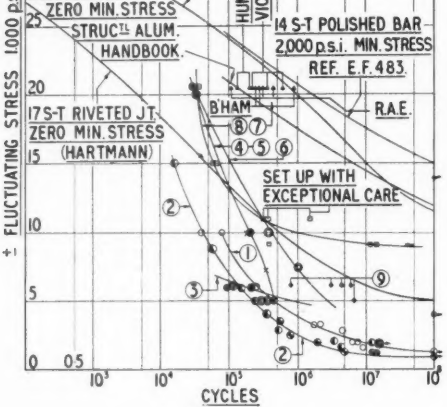

Fig. A.

Summary of basic fatigue test results.

Tests on a Haigh machine, on coupons cut from the web of the extrusion, were in hand and were giving results as low as 60 per cent. of the polished bar.

Until those results were satisfactorily sorted out and thoroughly understood, several interpretations were clearly possible. The two most obvious were a warning against a too facile acceptance of polished round bar results for design use, and against an unqualified acceptance of a given testing technique.

He did not think the position was quite so serious as his "extreme pessimism" limit; but the Society and Dr. Walker had given a lead which undoubtedly the Ministry and the Industry should follow. A concerted effort must be made to provide sufficient evidence for the designer to interpret his results rationally.

He thought that fatigue would never become a requirement in the same sense as static strength and stiffness, inasmuch as they gave design loads, but that certain forms of structural design would have to be rejected in favour of others that had better fatigue properties. In other words, it was too much to hope that the designer would ever achieve an aeroplane that had a precisely defined operational life, as well as being efficient in all other respects. The most that could be expected was that, all other design requirements considered, the life should be the longest possible.

K. T. Spencer (Ministry of Supply, *Fellow*): No one had mentioned the possible importance of the effect of temperature on fatigue life. The ambient temperature throughout the greater part of the flying life of the aircraft with which the meeting was principally concerned—and he agreed with Dr. Williams that those were the long-range civil aircraft—was likely to be low. A temperature of −30°C. was certainly not a low estimate; and if present plans matured and air liners of the future were to fly at 40,000 ft., the temperature would be much lower than that. It was surprising, therefore, that so far as he knew, all the experimental work was being done at room temperature.

It was true that a great deal of work had been done already on the fatigue life of materials at low temperatures; but they must pay particular attention to Dr. Walker's warning that the behaviour of a material itself was not an adequate guide to the behaviour of a structure made of that material. Presumably Dr. Walker was making that point with reference to behaviour at room temperature, and it might be that, even though he were able to establish a reasonably satisfactory correlation between the properties of material and structure at room temperature, the same correlation would not hold at low temperatures. He urged that the research should take account of very low temperatures.

Air Commodore D. F. Lucking (Civil Aviation Representative, Ministry of Supply, *Fellow*): Had the author any evidence of the effect of rate of increment of load on the life of a structure? Did a structure fail at the same number of repeated applications of load, irrespective of the rate at which they were individually applied? That was not quite the same as frequency of loading. It was well known that the elastic limit of some materials rose with the rate of loading and might even approach the ultimate stress. Did that mean that a high-speed aircraft, which presumably would be loaded very rapidly, might have as long a life in terms of flying hours as would a slow one? Would the fast aircraft withstand the rapid increment of load in a better way than a slower aircraft would withstand the same increment of load applied at a slower rate?

As an illustration of the well-known effect of rate of loading, he recalled some research

which he did as a small boy, when he had made bows and arrows. He had found that, when he drew back the bowstring quickly and released it immediately, the arrow went farther than when he did the same thing slowly. He had thought it might be because of his having unwittingly drawn back the string farther when he had performed the movement quickly. Therefore he had marked the arrow near the head and did a series of tests with the same length of pull. The result was the same as before, indicating that the bow yielded if bent slowly, but remained elastic if bent quickly to the same extent. He could not pretend to have understood his observations at that time, nor to have maintained his juvenile curiosity to the point of investigating the effect of rate of flexure on the life of the bow—usually abruptly ended by an irate parent or neighbour!

W. G. A. Perring (Director, Royal Aircraft Establishment, *Fellow*): They were really waiting on the physicist to produce a basic theory and framework into which the work on fatigue would fit. He believed that an understanding of the problem could only come from a fundamental approach of this kind, and in the absence of a theory the engineer would have to continue to fit the results into some reasonable pattern as best he could, to enable the work to be applied in a practical way.

Some rather empirical approaches had been made, which, by taking account of the rate of loading as well as the static testing work, had attempted a generalisation of the results of tests and had embraced static, creep and repeated loading. That kind of work did not advance their understanding of the problem, but he would like to have Dr. Walker's views on its usefulness.

In considering fatigue, one disconcerting feature was the wide variation in test results, as shown, for example, by the curves shown by Mr. Pollicutt. Until this work was understood, polished bar tests would have rather academic value, and it was doubtful whether they could be used, when considering the applications to aircraft. Equally disconcerting were the fatigue results being obtained on shaped sections compared with values measured on simple bars of the material.

The fatigue problem of the aircraft structure became even more difficult since a large number of other factors were introduced. Some of those were due to design; the presence, for example, of large joints, large cut-outs, the introduction of large extrusions or of castings into the structure.

Workmanship might also play a large part; the tightness of bolts or rivets could assume great importance.

Then again, the actual behaviour of the aircraft in flight might set up "local" conditions, resulting possibly from mechanical or aerodynamic disturbances.

On top of those difficulties, there was also the "cumulative" law.

He wondered whether any generalised or laboratory test on the airframe was likely to lead to really useful practical results.

What basis was there for supposing the cumulative law would apply? It was rather surprising some check of the law had never been attempted on steel, and if it worked for steel was it likely to work equally well for the light alloy?

He would like to share Dr. Williams' belief that all their troubles came from gusts, but it seemed there were equally important sources of trouble built into the aircraft and likely to remain with it throughout its life—vibration arising from the engine or propeller, or from the propeller slipstream passing over the wing or tailplane; buffeting due to the wing wake passing over the tail; difficulties due to wing root or wing nacelle junctions.

All of those could and did give rise to fluctuating loads that cumulatively might be serious. This brought them back again to the question—would they succeed in designing an all-embracing laboratory test which would be representative of those flight conditions of the aircraft?

Dr. Walker's suggestion for a "flight fatigue model" was interesting, but when account was taken of the load and vibration conditions at every point, and in every direction on the aircraft, it seemed likely the model might become a full-scale reduced strength model of the aircraft built inside itself. The idea behind the suggestion was good and should be followed up and worked out in practical detail.

N. E. Rowe (British European Airways, *Fellow*): Had tests been made on simple structures which previously had been proof loaded, and how did the results of such tests compare with those which could be obtained from the same simple structures when tested at comparatively low load without proof-loading? A great deal might be done by a

settling-down process, if they could arrive at one in which all the local yields would have occurred, so that they could have a structure in the state in which it would be towards the end of a fatigue test; in other words, when there had been a redistribution of stresses which made all the local fatigues less intense and definitely less dangerous. Was there a possibility of applying such proof loading to the various components of aircraft before they flew? It might introduce difficulties of loading; but he had been impressed by the suggestion that there was a redistribution of stresses as the loading increased, which redistribution very much modified the fatigue effects.

In Section 6.4 of the paper the statement was made that:—

> "Primary load is increasingly being diffused over thin sheets or transmitted to components (stringers, stiffeners, and the like) with thin sections, the whole being connected together by innumerable rivets. Thus the effect of working in material (light alloy) with inferior fatigue properties is being aggravated by the introduction of more stress concentrations."

He understood that that was exactly what Dr. Williams was asking them to do, and it seemed to lead to a more homogeneous structure and, therefore, one likely to be better from the fatigue point of view. Would Dr. Walker explain his view that it was likely to lead them into greater difficulties than they had already?

R. H. Chaplin (Hawker Aircraft Ltd., *Fellow*): The effects of genuine fatigue did not frighten him in connection with fighter design—he excluded fatigue failures due to vibrations arising from resonance, in secondary structure and minor fittings, and so on—for he had yet to see genuine fatigue failure in that class of aircraft. That was probably because the average life of such aircraft was not more than about 350 hours, with perhaps 700 hours as a maximum; he believed those figures were fairly representative, although he had heard of one case of a fighter flying for 1,000 hours. Fatigue which was not a source of worry in aircraft having so short a life might be quite serious in aircraft having lives of 10,000 and even 20,000 hours, which he believed were envisaged for civil aeroplanes. The problem became worse for the larger aircraft, which included civil aircraft, because obviously they operated at a much higher percentage of their ultimate strength than did the fighter aircraft, which was designed initially to much higher flight factors.

What was the author's opinion of the effect on fatigue of an initial application of stress above the proof stress during the manufacture of a component? That was apart, of course, from the possibility of residual stress. Did such an initial application of stress affect the fatigue life? He had in mind specifically the manipulation of light alloy, such as extrusions, in the fully aged condition, by the aircraft manufacturer—although the effects of work on the metal in trueing and straightening it at the material manufacturers were also important.

Was there any relationship between stress corrosion or inter-crystalline corrosion and fatigue failures of light alloys?

W. A. P. Fisher (Structures Department, Royal Aircraft Establishment): Whether fatigue was a real menace or merely a bogey, it paid to do everything possible to diminish stress concentrations. That would increase safety, and by paying more attention to small design details it was possible to increase fatigue life very much. He felt that that point had not been sufficiently stressed until now. Moreover, rather than make a joint several times as heavy as it need be, it should be looked at from the other aspect and made even lighter for the same fatigue strength.

One favourable factor of a large number of very small vibrations was the shape of the $S-N$ curve for a typical joint, as in the example shown by Dr. Walker. If materials were tested without stress concentrations and alternating stress were plotted in the usual way against the log of the cycles, it would go on descending right beyond 100 millions; with the stress concentration it would come down lower, but the slope became very very small indeed beyond 5 million cycles, and in many cases it was difficult to find out in a test what that slope actually was. Therefore, the increase of life when the alternating stress came down from the value at the bend of the curve to half that value would be enormous. That was a fairly general rule, he believed.

Metallurgists should begin to consider rather more realistic fatigue tests for materials, in the way of testing materials as nearly as possible in the form in which they would be used. He agreed with Mr. Pollicutt that the round bar test could be misleading. At all events, on a 32 tons per sq. in. alloy extruded section some tests were conducted

on the Haigh machine with plain flat specimens, and with specimens having a hole giving the theoretical stress concentration of 2.65, and the material in the extruded form came very far below the polished bar. Light alloy specimens to various specifications with the hole in them showed a fatigue strength reduction factor* in one case of about 1.5, in another case of 2.0 and in another case of 3.0. If the 1.5 specimen were compared with polished bar, it would be 3.0. Those high factors seemed to indicate that the full stress concentration effect should be allowed for, in accordance with the design rule given by Peterson in "Experimental Stress Analysis," Vol. I (1943), Pt. I, 118-127.

Dr. Walker had referred to the possible effects of load concentration in the structure as a whole, but it was also equally serious in local details such as unequal loading on different threads of a bolt or between different rows of rivets. Thus, there was in general stress concentration which was a combination of several factors, and it could be represented as:—

$$F_L \times F_{G1} \times F_{G2}.$$

There could be a geometrical stress concentration factor F_{G1} due to a stress concentration in a particular plane; in some joints there was also another stress concentration F_{G2} in the opposite plane, and the two might combine. The stress concentration was often aggravated by local load concentration F_L. The fatigue strength of a bolted joint, if it were only just finger tight, would come down to something very small indeed. The theoretical factor F_{G1} for a fillet adjacent to a loaded thread would be about 3.4. The factor F_L for the load concentration on the first thread in the bolt might be about 2. This would halve the fatigue strength of the bolt (as compared with an ideal bolt in which all threads were equally loaded) unless something were done in the way of pre-tensioning it in order to relieve it of the alternations of load. Pre-tensioning was the condition of use which saved bolts in tension from fatigue.

Another possibility with regard to bolt threads was the improvement of strength by thread rolling; but tests had shown that, in order to secure improvement, it was necessary that the rolling should be done after heat treatment. Rolling before heat treatment was of no benefit.

H. Davies (Bristol Aeroplane Co. Ltd., *Fellow*): From the metallurgical point of view, what was the nature of the catastrophic change of structure which set in at fatigue failure?

What relation existed between the elongation of a material and its fatigue properties? In general, the steels and light alloys showed a reduction in elongation with increasing ultimate tensile strength; did the fatigue properties suffer in the materials in the higher tensile ranges?

An intriguing point was that wooden structures showed no susceptibility to fatigue; why?

In certain forms of reinforced timber structures, such as a certain type of airscrew blade, the material was extremely brittle, very notch-sensitive; yet the end of the airscrew blade was threaded in a rather vicious manner into the airscrew hub, and the stress concentration around the edge of the thread was very high if the thread were absolutely square cut. There was a high stress at the end of the airscrew blade and, furthermore, a stress which was reversed a large number of times. Yet fatigue failure did not occur there.

During the war almost all American aircraft engines had had a standard type of welded engine mounting. The limiting fatigue stress for a welded joint in almost any structural steel appeared to be of the order of 10 tons per sq. in. There was no part of an aircraft structure which, he imagined, should be so susceptible to fatigue failure as was an engine mounting, for there was constant vibration throughout the life of the aircraft, and the engine mounting was presumably stressed to something of the order of 40 tons per sq. in. So that it was working to a stress considerably higher than the fatigue stress of the material, which was subjected to a large number of vibrations. That should give them some cause for comfort. He would have said that, if any structure should have failed under fatigue, it was the American welded engine mounting; but for some strange reason it did not.

W. L. Cowley (Structures Department, Royal Aircraft Establishment): They had made accelerated tests with materials at 1,000 cycles per minute and up to 5,000 per second without finding any substantial change in fatigue properties. But in structures they had at certain points stress concentrations in the neighbourhood of the yield point of the material, and it seemed

* *i.e.* the ratio of fatigue strengths with and without the hole.

that for that reason it would be impossible to devise accelerated tests which would give adequate data on a reasonable programme within a reasonable time.

He was rather disturbed by the fear that the wealth of data they had relating to materials would not serve them very well in regard to structures. It was obvious that when the stress was applied at high frequency, there would not be sufficient time for the material to be disturbed in the same way as when it was subjected to stresses in the neighbourhood of the yield point under very slow fluctuations. It seemed to him that their only hope was that those of the more optimistic frame of mind, who held that fatigue was not really so serious, were right. If, on the other hand, fatigue were really serious, then he feared they had trouble ahead.

Dr. H. Roxbee Cox (President and Chairman, *Fellow*): He had always admired Dr. Williams' complete mastery of the laws of nature. Indeed, he had felt that if Dr. Williams came across a law of nature which he did not like, he would repeal it! Consequently, it was with some trepidation that he had decided to disagree with Dr. Williams. He could never understand the point of view that loads above 50 per cent. need not worry them. Certainly it was true they did not do so very often; they did not have to! There could be one thumping load of 75 per cent. of the total, and they "had had it"! He implored Dr. Williams not to ignore the importance of the higher loads; they might not occur very frequently, but they had very noticeable effects when they did.

There was a great deal in Mr. Perring's point about going to the physicist for some basic work in connection with fatigue. He wondered how the electrical properties varied in a material which was getting near the fatigue point. If they did vary in that region there might be some hope for the sort of tell-tale for which two speakers had asked. It was important also that they should collect as much statistical information as possible.

Looking back over the history of aircraft as he had known them, he felt that their record in respect of failure from fatigue was extremely good; he would regard the probability of failure from fatigue as being low. Nevertheless, they should know more about it, and it was most important to collect statistics on the past history of aeroplanes which had done long flying service.

F. Grinsted (Structures Department, Royal Aircraft Establishment, *Associate Fellow*) *contributed*: Broadly speaking most aircraft had been designed solely for single applications of ultimate loads reasonably greater than the greatest loads expected in flight. It was largely good fortune that this procedure had also provided fatigue endurance for many applications of lower loads. Already, however, it was necessary to assume higher ultimate factors on known maximum loads than occurred many times—such as catapulting loads—not because higher ultimate strength itself was needed but to raise indirectly the fatigue endurance.

If automatic devices for restricting manœuvring acceleration and speed were ever used load-frequency curves would have "flat-topped" peak loads; fatigue failure would then be encouraged unless the ultimate factors on the peak loads were chosen to be higher than were now customary for intrequent loads.

Some modern trends would accentuate fatigue by imposing a high mean load about which the usual fluctuating aerodynamic and mechanical loads would operate. One example was the high inflation pressure in cabins. Another was the tendency to cruise at speeds near the maximum design speed, thus in some cases subjecting the tail structure to a high proportion of its ultimate load for long periods. These trends might demand the use of higher ultimate factors until sufficient was known for structures to be designed directly to have endurance for the load cycles they would experience.

J. A. C. Williams (Heenan, Winn and Steel, *Assoc. Fellow*) *contributed*: The discussion had focused attention on the shortcomings of double heat-treated aluminium alloys from the "notched" aspect compared with their unnotched static strength. This disability had been attributed to magnesium alloys in the past but it was probable that the modern magnesium alloys were better than the aluminium alloys in that respect. With magnesium-zirconium castings (D.T.D. 721) notched and unnotched test bar figures gave the same value at 50×10^6 reversals of ± 5.75 tons/in.^{2}; those figures in themselves were an interesting commentary on the relation of fatigue (with notched and unnotched conditions) and elongation because the minimum specification elongation was 5 per cent. In sheet structures subjected to heavy fatigue loads the

magnesium zirconium sheet had shown no predilection to fail at the rivet joints or deliberately introduced cracks. Again, the magnesium alloys had a flatter S vs. n curve than the aluminium alloys at reversals in excess of 10^6. In view of those facts it behoved designers to investigate more thoroughly the claims of the latest magnesium alloys in actual structures subject to fatigue loading. Dr. Walker had suggested a re-examination of steel applications, but ignored magnesium without cause—a view in which the U.S.A. did not join.

In practice, especially with control surfaces and light aircraft there was a tendency for drumming to take place in panels; this resulted in cracking at places where changes of stiffness occurred, such as rivet lines, but the cracks were away from the rivet heads themselves. The paper did not explicitly mention this point, but it was important.

Helicopters were not dealt with at all but they must be designed and maintained by fatigue standards. In them ball bearings were used in a structural sense and an economic problem was then posed by fatigue. Oversize bearings could be installed which would last for the anticipated helicopter life but cut down payload and increase first cost slightly or, smaller bearings could be installed which needed replacement after a stated time and thus increased maintenance cost. In helicopter design an interesting comment could be made on the foregoing remarks: in the rotor blades of both rigid and feathering types minimum size, fatigue and flexibility dictated and they would probably see a departure from the wooden blade to a steel type; in the fuselage structure, panel rigidity and simplicity were required and magnesium alloys were ideal. Wooden blades could fatigue (this answered Mr. Davies) but the type of failure was generally different to metal and design flexibility requirements normally precluded fatigue failure. In wood, delamination along the fibres took place and especial care should be taken at changes of section. In airscrew roots high density compressed wood was used and although fatigue loads occurred the main stresses were centrifugal. Those were taken not by square threads but by an Acme type cut on a taper, so that there was a spreading of load across the root fibres.

J. B. B. Owen (Royal Naval Scientific Service, *Assoc. Fellow*) *contributed*: In designing aircraft to lower and lower load factors, unless oscillatory loads due to gusts, engines, landing, etc., were lowered, the incidence of fatigue might be expected to increase. During the last war fatigue failures occurred on fighter as well as bomber aircraft and defective detail design seemed to be the factor most responsible for the defects which arose. The defects could be classified, as Dr. Walker suggested, into two groups, those which could be detected before catastrophic failure occurred and those which were very difficult to detect before catastrophic failure occurred. In the former group were skin cracks developing from rivet holes, for example; in the latter, fatigue failure of a spar boom at a joint. Such catastrophic failures must be avoided.

Designers employing concentrated booms might well need to be very careful of their detailed design since detecting trouble at an early stage might be difficult, but those distributing loads through a reinforced riveted skin should have more chance of spotting defects before they resulted in catastrophy. Therefore he was puzzled as to why Dr. Walker, in his concluding remarks of paragraph 6.4, was so concerned with this latter practice. Had catastrophic failures of the kind encountered in some types of welded ship also occurred in aircraft structures?

W. E. Cooper (Fairey Aviation Co. Ltd., *Fellow*) *contributed*: The dominant design considerations for many years had been aerodynamical efficiency and increased speed of aircraft, with the general assumption that materials' behaviour and static load conditions would prevail as usual. Prospects of higher speeds—even 12 or 15 years ago—were adequate warning that ultimately aircraft engineering would become involved in the fatigue problem, just as other branches of engineering had done. In fact, occasional fatigue failures of small fittings had already appeared at that time.

To those who had interested themselves in, and contributed to, the subject in the field of metallurgy and the many other branches of engineering, the author's views were noticeably partial in emphasising the almost useless application of present knowledge of fatigue to the aircraft designer's problems. While regretting the present situation, the metallurgist and research engineer would point out the apathy and lack of foresight on the part of aircraft designers, when much earlier attempts were made to initiate interest in the subject. The late Professor F. Bacon had

been introduced to several aircraft centres, before the war, with the same objective. The author omitted reference to the many cases in other engineering branches which had benefitted from the classical contributions on fatigue, including the major factor—stress concentration.

Since aircraft structural parts were, in the main, heterogeneous systems, consisting of riveted and pin-jointed combinations of unlike materials (most probably studded with stress concentrations), it was hardly to be expected that the approximate rules derived from investigations on homogeneous metals and elemental engineering parts would apply. Investigation of the behaviour of such heterogeneous systems under the complex load conditions involved had, therefore, been an obvious task specific to the aircraft designer, and the author had justifiably elaborated upon this aspect.

It would not be generally agreed that the use of higher fatigue strength materials was the necessary solution to the present problem until it had been demonstrated that stress concentration in design was at a practical minimum. Again, it was not clear how knowledge of the basic nature of fatigue could be applied to elucidate the intrinsic fatigue strength or life of the structural (combination) part. The ingenious suggestion to attach a miniature test structure to an aircraft in flight would appear to involve " scale effect," which would render translation of results into full-size quantities a questionable matter.

H. F. Winny (Fairey Aviation Co. Ltd., *Fellow*) *contributed*: Dr. Walker referred to the discontinuity of slope as the mean load M changed from positive to negative in Fig. 7. If the assumption were that the compression properties were the same as the tension properties in fatigue, those curves need have no discontinuity. Could Dr. Walker give any information on fatigue failures in compression to support, or otherwise, the assumed symmetry of the diagram about the axis $M=0$?

The author suggested that where the elastic limit of one part of a structure was appreciably exceeded before the general elastic limit of the structure was reached, this should be condemned as " bad design." In modern aircraft structure it was extremely rare that such a feature could be avoided if an efficient design were to be achieved. As an example, the web of moderate grade plate (*e.g.* D.T.D. 610) riveted to a high grade extrusion (*e.g.* D.T.D. 363) could be quoted. The web adjacent to the extrusion would receive permanent deformation at an appreciably lower load than the extrusion under direct load. It was suggested that such construction should not be dismissed as " bad design," but that it would have to be investigated since up to the present it had proved satisfactory.

The suggestion of a miniature structure was interesting but in view of the fact that scatter was an essential feature of fatigue it would be difficult to put into practice unless several structures were carried and then the scatter of the aircraft itself would have to be considered. The method assumed in fact a complete knowledge of the fatigue properties of the aircraft before the miniature structure could be designed.

What type of riveted joint was used on Fig. 10, and did corresponding data exist for snap head rivets, cut countersunk rivets and drawsunk rivets?

How would grain flow influence the general results of Fig. 10?

Dr. H. Sutton (Ministry of Supply, *Fellow*) *contributed*: It was a general feature of high strength wrought aluminium alloys commonly used in aircraft construction that they did not show such a well-defined endurance limit as the usual engineering steels. Some of the medium strength aluminium alloys and also some magnesium-rich alloys showed a more pronounced limit, however, and this feature might assume increasing importance as further experience was gained.

Dr. Walker had mentioned the ability of certain types of ferrous material to recover at normal and slightly raised temperatures from the effects of applied stress cycles. Several investigators working quite independently had noted the improvement in endurance in ferritic steels under interrupted fatigue tests compared with that observed in the normal continuous tests. Although the same effect had been looked for in aluminium alloys by Bollenrath and others it had not, to his knowledge, been observed to occur in those materials, suggesting that there, at least, the effects of fatigue cycles applied at intervals were indeed cumulative. The differences between the two classes of material seemed to offer a ray of hope that non-ferrous alloys could be developed which would show similar features in lack of " fatigue-memory " to the ferritic steels.

Dr. Walker mentioned large numbers of rivets being used to connect together thin sections. Many cases were known in which large numbers of stress raisers were apparently less dangerous than solitary ones, a feature well brought out by corrosion fatigue work of Simnad and Evans at Cambridge. At the same time there might be need for riveted joints which were stronger than those at present used. Cladding of sheets did not seem to decrease the fatigue strength of riveted joints at the lower endurances but under conditions of high fatigue stress tended to improve them, possibly due to relaxation of high skin tensions such as would not so readily occur on unclad sheets. Dr. Walker's reference to local stress concentrations and permanent deformation at riveted joints was very appropriate. Did he feel that the permanent strain arising in the riveting operation played an important part?

Many of the features of fatigue were discussed in the Symposium on the Failure of Metals by Fatigue, University of Melbourne, the papers and discussion of which had been published by the Melbourne University Press.

Two features of fatigue which were liable to be overlooked were the reduction of fatigue resistance by corrosion and corrosive influences, and the reduction by fretting, probably also associated with chemical influences of the atmospheric gases and moisture on the activated metal surface. In both cases the effect could be a substantial one. On most structural materials except stainless steels the protective treatments and paints used probably contributed appreciably to the endurance of the structures under the conditions of service.

Dr. Walker's plea for means of annealing structures *in situ* was appreciated. A convenient means of heat-treating light alloy assemblies would be very useful but seemed unlikely to prove possible for very large assemblies. Mist-quenching had possibilities but distortion at heat-treatment temperature and during quenching would seem to preclude the possibility of dealing with large assemblies in this way. He was glad that Dr. Walker mentioned gluing as an important development as that seemed to be one of the most promising methods of obtaining joints free from locked-up stresses and overstrain. He hoped Dr. Walker would be able to review the subject again later when there was more experience of the endurance of aircraft structures under modern conditions of use.

L. Rotherham (Royal Aircraft Establishment) *contributed*: Dr. Walker had gone a long way to remove the obscurity which had existed in this subject by clearly labelling it "fatigue" and pointing the analogy with the fatigue of metals. From his account, the fatigue of structures was the same phenomenon as the fatigue of metals but in one degree more complex due to the complexity of the structure. Bearing in mind the fact that metals were rather heterogeneous themselves this was not such an excessive addition to their difficulties.

He wondered if Dr. Walker had gone far enough with his comparison with fatigue of metals. He would like to draw attention to some of the observations on metal specimens to see whether some of them might help to suggest ideas in relation to the testing of structures.

When a safe stress had been exceeded in a metal specimen, a crack might appear after a few hundred cycles of stress and the major part of the life of the specimen was spent in the spreading of the crack. This corresponded to the case mentioned by Dr. Walker, where one member failed without causing catastrophe to the whole structure. They had observed that a specimen might crack but the crack was deflected by some feature in the structure of the metal so that it tended to run parallel to the principal stress and then did not spread further. As many as ten or more cracks might form one after another in a single small specimen, only one spreading to cause failure in the metal. He wondered if it were possible to design structures which would block the spread of a crack, possibly by building up thicker members from layers of thin sheet? Laminated plastics were an obvious possibility.

Structural engineers could assess the possibility also of building stresses into a structure as they were introduced into metals by processes such as nitriding or shot-peening. The process of nitriding was one to introduce a material of high resistance to fatigue in compression and to place the material in a state of compression from the beginning with very beneficial results. There might be cases where it was desirable to build internal stresses into a structure deliberately to increase its fatigue resistance.

Dr. Walker referred to the advantages which might occur from cyclic loading below

the fatigue strength due to the shaking down of the structure. The same result could be achieved in metals and a similar effect could be obtained in a shorter time by over-stressing for a few cycles. Perhaps the same method could be applied to a structure.

It was generally assumed that notch effects were more pronounced in hexagonal metals than in cubic metals and it seemed that this might be because they had fewer glide planes, that is, there were more geometrical restraints to plastic flow. Like metal crystals, aircraft structures often had a symmetrical structure and he wondered whether there were different types of symmetry, some of which would be preferable for avoiding the onset of fatigue.

Studies had been made of the variation in internal friction of metals during fatiguing. In some alloys the internal friction decreased as fracture was approached, while in others it increased. For resonant vibrations with a small driving force the first condition corresponded to a decrease in safety with time and the second to an increase in safety since the amplitude of the vibration increased or decreased progressively with the damping. In metals they took the damping they were given until they could understand the process better but in structures he would have thought that mechanical damping might be introduced into the design to deal with the growth of forced vibrations. Whether this was true or not different constructional methods would have differing effects on the damping and therefore on the fatigue life of a structure.

It might be thought that these comments were of a kind to suggest that he was trying to tell the structures experts how to carry out their difficult task. Nothing could be further from his intention and he disclaimed any real knowledge of aircraft structures. While he accepted Dr. Walker's conclusion that tests on complete structures were no doubt necessary at the present time and might be all that was ever necessary for practical purposes, he doubted if a full understanding of the results would be possible owing to their complexity. He felt that some idealised structure intermediate between a metal specimen and a full structural component should be tested in addition, if such a test could be devised, before they could hope for a full understanding.

DR. WALKER'S REPLY

The President had intimated that they all seemed concerned about the danger of fatigue, but much depended on what they meant by "danger." Were they looking at the problem from the point of view of the person in the aircraft or from that of the person who made the aircraft, or of the person who sold it or of those who lost money if the aircraft were not successful? He thought the real dangers were economic, and that what they were worried about was that aircraft might not last sufficiently long. There had been references to the danger of catastrophic failure; but everything pointed to catastrophic failure being unlikely. One of the reasons they were becoming concerned about fatigue was that they were producing failures in the laboratory which were warning them of possible troubles in advance. So that really the danger of unforeseen fatigue failure occurring in the air was not nearly so serious as most people thought. It was quite another matter if they had to take aircraft out of the air because they were not safe to fly any farther.

Mr. Howard: The more detailed problems in aircraft structural fatigue were at present almost beyond the comprehension of any one individual. The research and experimental work required, moreover, undoubtedly exceeded the resources of any one research and development organisation. Only by the pooling of knowledge and experience could they expect to overcome the immediate design difficulties with which they were faced.

He thought the prospects for a cumulative rule for fatigue of aircraft structures were poor, but the fatigue indicator warranted careful study. Both this and the possibilities of a tell-tale device or fatigue indicator to give advance warning of fatigue failure were discussed in greater detail later.

Mr. Gardner: Mr. Gardner's views were based on an exhaustive study of fatigue made on realistic lines, backed by experimental work of high quality. His pessimism appeared to be a state of mind reached by many research workers in fatigue at some time or other. In actual fact, it was the kind of work which Mr. Gardner and others were doing which provided the main grounds for optimism and for the belief that the immediate design difficulties would be overcome in a practical way.

Dr. Williams: The task of restricting the field of enquiry to the more urgent problems was one to which Dr. Williams had given considerable thought and it was essential if the more important problems were to be dealt

with first, and if unnecessary dissipation of effort were to be avoided. Unfortunately this was a subject on which there was a wide diversity of opinion. Several speakers were less willing than Dr. Williams to concentrate only on large aircraft, to the exclusion of other types, particularly fighters.

Dr. Williams had suggested that in addition to taking the usual precautions against fatigue failure in the first place, further steps should be taken to provide a structure which, after the first fatigue failure, was still able to carry steady loads in level flight. In other words precautions were to be taken to ensure that the aircraft could complete its journey or return to base provided no undue hazards were encountered on the way. It would be interesting to develop this approach to the fatigue problem further.

Mr. Pollicutt: The factual data supplied by Mr. Pollicutt were the kind they liked. The somewhat disappointing results were perhaps at first sight disturbing, but were their demands and expectations too exacting? Would tests on earlier aircraft components, where fatigue was not considered a serious danger, be very different? It was possible that the fatigue loadings occurring in flight were not so serious as was generally supposed. It could scarcely be claimed that such tentative requirements as had been so far proposed were based on solid evidence.

Mr. Spencer: The possible effects of low temperature on structures must be remembered. Most light alloy materials at present in use had fatigue properties which improved with lowering temperatures, and there were no reasons to suppose that the effect on structures was adverse. As Mr. Spencer pointed out, one of the main themes of the paper was the need for study of structures as distinct from the materials of which they were composed. Any broad generalisations of temperature effects on structures might therefore be dangerous in the absence of real evidence, and that evidence must be obtained. Plans had already been made to carry out such tests at the Royal Aircraft Establishment. The reasons why results were not yet forthcoming would be understood by all those who had experience of the time required to make fatigue tests on structures, and the need for many repetitions to establish the extent of variation between nominally identical specimens.

Air Commodore Lucking: For metal aircraft structures rate of loading as occurring in practice did not appear to be a significant variable in the determination of fatigue life. Allowance had to be made, however, for any inertia forces with which a high rate of loading might be associated. There might well be an apparent change in response to fatigue loading through the applied forces being modified by the inertia forces.

Inertia forces imposed a limitation on the extent to which fatigue tests might be speeded up, although at high rates of loading it might be difficult to distinguish inertia effects from any direct change in fatigue resistance such as Air Commodore Lucking mentioned.

The account of experiments with a bow and arrow was interesting. Presumably, however, the bow was made of wood, several structural properties of which had a time factor not possessed by metals to anything like the same degree.

Mr. Perring: Much more work on the fundamental nature of fatigue as a materials phenomena was undoubtedly essential if the design of aircraft from the fatigue standpoint were to proceed on a rational basis. Without knowledge of what really constituted fatigue the engineer and designer were having to make bricks without straw. There were one or two points which might be brought out, since Mr. Perring voiced the concern of several workers in fatigue.

In the first place, metallurgists and physicists were fully alive to this need, and work was proceeding which was of no less value because it was proceeding quietly. He had taken pains to ascertain that this was so before preparing the paper. The engineer was not waiting for such information, but was making the best use of whatever information was available.

Possibly Mr. Perring was slightly misunderstood when he said " they were really waiting on the physicist to produce a basic theory," but it was worth while to have clearly in mind that engineers were not merely making the best of a situation but were actually making progress in spite of handicaps such as lack of fundamental knowledge. Finally, the empirical treatment of fatigue should not be regarded merely as a temporary measure. All the indications were that much the same approach would be necessary even when, as it assuredly would be, the fundamental problem had been solved. Fatigue of structures would always be a subject of great complexity, requiring

broad empirical treatment to enable reasonably simple design rules to be established.

He did not entirely agree with the condemnation of polished bar tests to the extent of calling them "academic." The fault lay in their application. The object of these tests was to establish properties which were specific to a material, and so there had to be eliminated all variables such as scratches which did not depend on the material. Such a course was necessary for comparison of one material with another. The effects of scratches, stress concentrations and the like might be different for different materials, but those could be investigated separately. Knowing what a material would do under ideal conditions was but a first step, but it was an essential one. From the concern expressed by Mr. Perring and by several other speakers there appeared to be no danger of designers being misled by the somewhat idealistic figures quoted for materials.

In expressing doubts as to the validity of any cumulative rule that had already been devised or which might be in the future, Mr. Perring probably expressed the feelings of all practical engineers. No workable rule had been established even for materials in their simplest form. With the complexity of the structural aspects of fatigue, the prospects for a useful cumulative rule were almost negligible.

There was no cumulative rule to check for steel, if they excluded those which could be dismissed as wrong from the start. For most steel structures there was ordinarily no demand for such a rule since the material was mainly used within its endurance limit and had theoretically an infinite life. Furthermore, even if a cumulative rule were to be sought it would be seriously complicated by the introduction of the time element involved in recovery from the less severe loadings.

He did not understand Mr. Perring's doubts on the value of laboratory tests on complete airframes. On general grounds there were reasons to believe that an aircraft type which had had a laboratory test for fatigue was much safer than one which had not. A modern aircraft structure was so complex that there was some excuse for the vulnerability of one particular part being overlooked. Furthermore, there was the hidden fatigue danger referred to in Section 4.5 which could not ordinarily be detected by any other means. Against those two dangers the fatigue test of a complete structure was the first line of defence, even though it could only be an imperfect representation of actual flight conditions.

Those were the minimum claims and he would go even further. There were grounds to suppose that a reasonably simple routine for testing could be evolved to give a great measure of protection against all reasonable foreseeable hazards.

The fatigue warning device was mentioned by several speakers, and appeared to be of sufficient general interest to warrant more comment than originally seemed appropriate in a paper ostensibly dealing with broad principles. As Mr. Perring suggested, the device was little more than the germ of an idea at present, but one showing promise for future development.

Reference to it as a "flight fatigue model" by Mr. Perring implied something more elaborate than was originally intended. The "tell-tale" of Mr. Howard or the "coupon" of Mr. Gardner were more appropriate since something quite simple was envisaged. The draft text of the paper was definitely at fault here in giving this wrong impression, and had been corrected.

The device was perhaps best regarded, not as a model of the aircraft, but as a simple calculating machine using a physical analogy that followed closely the behaviour of the actual aircraft. Into a piece of material or small built-up specimen were fed fluctuating loads that were directly related to those encountered by the aircraft. The device then carried out a process of analysis, not only dealing with laws that were too complex for direct analysis, but also with laws that were imperfectly understood.

The essential purpose was to indicate the way in which fatigue life was being consumed on the aircraft to a higher degree of accuracy than was possible by merely recording flying time. To achieve this purpose some form of calibration was required and the method of calibration would depend upon the type of indicator used. A simple example might conveniently be considered.

It was assumed that a complete structure was to be fatigue tested to failure in a laboratory for a loading sequence deemed to be the best simple representation of actual flight conditions. The difficulty with such a test was to interpret it in terms of permissible

flying time. To overcome this difficulty a number of strips were attached at a convenient place on the aircraft structure being tested, so as to pick up strain. The strips were designed to break successively during the test. When the aircraft structure failed in fatigue the last strip to fail was noted. A similar strip was then installed on operational aircraft of the same type together with weaker strips to give preliminary warnings.

This explanation gave the bare principles underlying the warning device, but indicated its possibilities. There was clearly plenty of scope for research and development. The greatest obstacle to success was that too much be expected of it. This risk could be overcome if it were regarded as a device which only went one degree farther than a simple clock in recording the passing of fatigue life.

Mr. Rowe: Pre-loading of new aircraft just before going into service had already received some attention. The advantages which might appear promising when considered on general grounds, tended to diminish when any scheme was examined in detail. The loading system on an aircraft structure as occurring in flight was not only complex, but varied considerably. By favouring one in the preloading process they might prejudice others and, even if the most appropriate form of loading were chosen, there was a danger of going too far and doing more harm than good. In the present state of knowledge it seemed best to rely upon the loadings normally occurring in the early life of the aircraft before fatigue failure could be regarded as a possibility.

Mr. Rowe appeared to be concerned at the suggestion that some of the more modern trends in design were detrimental to fatigue resistance. Evidence indicated that certain trends in design, directed primarily towards greater structural efficiency from the standpoint of static strength and stiffness, were prejudicial to fatigue resistance. Possibly this aspect was not developed as far as it should be in the paper but the subject was exceedingly difficult. Apart from the existence of local stress concentrations in the material, fatigue strength might suffer through bad stress distribution in the structure brought about by large holes such as were required for undercarriage stowage. Thus the known advantages of the monocoque principle, by which an attempt was made to ensure that all the material carried load, were marred by the principle having to be abandoned in certain places.

The adverse effects of such discontinuity were recognised from the standpoint of static strength, but the indications were that they were still more serious from the standpoint of fatigue. This did not necessarily mean that any particular form of structure need be condemned, but that in some cases extra static strength might have to be provided to avoid fatigue failure.

Mr. Chaplin: Mr. Chaplin's view that fatigue was not a major problem to fighter designers was interesting. There was a *prima facie* case for this, as stated by Dr. Williams.

A word of caution might be introduced at this stage, based on the conclusions reached in the paper. The hidden fatigue danger referred to in Section 4.5 could be insidious. Parts of an aircraft might be highly stressed at low load levels while escaping ultimate failure in a static test through permanent deformation. Possibly the danger might be rather less serious for fighters than for low-factored aircraft, but in general there was no correlation between the phenomena described and overall factors, and fighters could not be regarded as immune.

Furthermore, the favourable comparison between fighters and low-factored aircraft generally was largely based on the response to gusts. As Mr. Perring pointed out, vibration might produce results just as serious from the fatigue standpoint. Even if they excluded, as Mr. Chaplin did, pure mechanical vibration, there was the mixed vibration in which aerodynamic forces played a part. In extreme cases such vibrations might take the form sometimes known as incipient flutter; but even with only engine or airscrew excitation it was sometimes sufficient, under adverse conditions, for the aerodynamic damping of control surfaces merely to diminish in order to create a steady state of severe vibration. There were also cases of direct aerodynamic excitation such as high speed buffeting. In general all those adverse aerodynamic effects became increasingly serious with increasing speed. Thus what a fighter might gain through its high factors it might lose through its high speed.

Mr. Fisher: The fatigue behaviour of structures was a difficult subject to pursue, largely because there was a superposition of effects of widely different kinds. One or two aspects of the fatigue problem could be

investigated in a detached way, and merited intensive study even though immediate benefits might not be apparent. Foremost of these was stress concentration, a subject in which Mr. Fisher was specialising in some degree and in which he had a strong position through his extensive knowledge of photo-elasticity. One further demand they had to make of Mr. Fisher, and of all those engaged on work of similar character, was that they spare no effort to cast the results of their researches into a form which could be directly used by designers and engineers working in the wider field.

Mr. Fisher had raised one point of great practical significance. When discussing ways and means of improving fatigue resistance they should consider real cases whenever possible. Any change in fatigue characteristics must be studied with particular, or at least typical, endurance curves in mind. Thus, if a curve were virtually flat there was no purpose in expending effort in moving a small distance along it.

It was interesting that bolts were even more vulnerable in fatigue than was realised. It appeared, however, that pre-tensioning, generally regarded as a means of improving fatigue resistance of bolts in tension, merited further study.

Mr. Davies: The nature of the catastrophic change in internal structure of a material was the essence of the fundamental materials problem which had been mentioned several times, and for which there was no solution yet.

From the general engineering standpoint there was practically no correlation between the fatigue properties and any other properties of materials, although materials specialists might wish to qualify such a sweeping generalisation. It was interesting, however, that any improvements in ultimate strength which were achieved, as they often were, without corresponding improvements in fatigue strength might increase the danger of fatigue failure whenever static strength was made the primary consideration in design.

The behaviour of wood was intriguing to all who worked primarily in metals, but the question was why some materials were susceptible to fatigue rather than why some were not, which brought them back to the fundamental question of what happened to a material to make it fail in fatigue.

In the design of engine mountings fatigue was a primary consideration from the start. The severe vibration to which Mr. Davies referred did not as a rule give rise to the high stresses he mentioned, and the high stresses produced by other causes were much less frequent. Nevertheless engine mountings had given trouble in the past and might have to be considered again on broad general lines if there were any tendency to lengthen the useful life of aircraft appreciably.

Mr. Cowley: The presence of unrepresentative inertia forces had already been mentioned as imposing a limitation on the way in which fatigue tests could be accelerated. It was likely that there were other limitations, as Mr. Cowley suggested, and the effect of yield might introduce a time factor not ordinarily present in actual flight.

Mr. Grinsted: Aircraft had been designed in the past primarily from the standpoint of failure under a single application of load, but it was undesirable that too much should be read into this. Other effects had often been taken into consideration indirectly. In some cases a fictitious value for ultimate strength had been used, especially when it had been desired to cover the proof requirement without two sets of calculations. Perhaps more significant was the statistical basis on which required standards of strength were laid down. Based on years of experience of behaviour of aircraft, design requirements, even though expressed in terms of ultimate strength, must inevitably have been influenced by other considerations such as fatigue. The disadvantages were two. First, statistical data must be based on past aircraft and might not be applicable to those at present in use. Secondly the attempt to cover fatigue by controlling the ultimate static strength could be inefficient and lead to unnecessary weight. For those two reasons it had become necessary to study fatigue more fully in design, and when the fatigue risk had been eliminated it might be possible to relax on the requirements for ultimate strength.

The high steady loadings occurring on some aircraft, mentioned by Mr. Grinsted, were important, and might account for some of the failures experienced. Mr. Grinsted also pointed out the possible disadvantages of load restricting devices, such as gust eliminators or "*g*-restrictors," that were directed towards limiting the maximum load. Usually such devices did not operate uniformly over the loading range and were

more effective in curbing the higher loads. If the objective was to justify a reduction of static strength, therefore, the danger from fatigue was directly increased. There was a possibility, moreover, of such a device not being dead-beat in its action, and producing fluctuations of load at the lower levels which otherwise would not occur.

Mr. Williams: The claims made for certain magnesium alloys should not be forgotten. The paper mentioned the possibility of light alloys being developed with better fatigue properties for structural work, but on the whole it seemed desirable to avoid expressing opinions which might be premature.

Helicopters did not come within the scope of the paper, although they presented a most interesting problem in design for fatigue resistance.

Mr. Owen: His emphasis on the value of preliminary warnings was not out of place, but the economic effects of fatigue should not be forgotten. Even non-catastrophic failure could be serious if it led to an unacceptably short working life, or to prohibitive cost in inspection, repair, maintenance and replacements.

Mr. Cooper: The preliminary enquiries which the author made before writing the paper did not support Mr. Cooper's belief that the Aircraft Industry was guilty of apathy and lack of foresight in dealing with the aircraft fatigue problem. It had to be remembered that fatigue was only one of many difficult subjects which the designer had to investigate, and on the whole the distribution of effort to the various adverse phenomenon which an aircraft encountered had been extremely well controlled.

Mr. Winny: Where material had symmetric properties there must be a discontinuity of slope in Fig. 7 at zero mean unless the slope was zero. The slope could not be zero, however, in the limiting case of a single loading to destruction which provided the upper boundary to the diagram. Hence a discontinuity, or sharp curvature amounting to a "virtual" discontinuity, was to be expected somewhere in the field. The point at issue was in some respects academic, but such theoretical considerations could be a great help in drawing curves through an inadequate number of experimental points. It was interesting that many materials had continuity of slope at zero mean load, without the slope being zero, because their properties were not in fact symmetrical in respect of tension and compression.

He had intended to acquit designers of "bad design" in certain cases of premature yield, and not to condemn them. The main point about the hidden fatigue danger of Section 4.5 was that it was not in the ordinary way foreseeable without an actual fatigue test on the complete structure. The whole situation revealed how shaky was the basis of the proof load requirements. Permanent deformation on a large scale might readily be recognisable, but for individual components it might be undetectable by ordinary means. Furthermore, on a still smaller scale, such as occurred in a riveted joint, permanent deformation was essential to the proper functioning of a structural component, and the proof load requirements had to be deliberately ignored.

Perhaps his reply to Mr. Perring answered some of Mr. Winny's queries about the fatigue indicator. There was one other point not covered. Scatter in fatigue properties of aircraft structures, that was variations in nominally identical structures, was not properly to be regarded as a limitation in the functioning of the device, being common to all methods of controlling the allowable life of an aircraft.

Dr. Sutton: It was not an easy task to present a review on structural fatigue, deliberately emphasising the structural problems, and yet do justice to the purely materials aspect. It was reassuring to find a materials authority like Dr. Sutton showing no marked disagreement with the way the materials problem has been dealt with.

Some encouragement was to be obtained also from Dr. Sutton's reaction to certain suggestions for improvements in materials that appealed especially to the structural engineer. Thus they did not yet need to dismiss as impossible improvements in light alloys to produce, at least in some degree, fatigue properties already possessed by some steels. Even the annealing *in situ* of parts of a structure appeared to be worth serious consideration, although the practical difficulties were obvious.

The absence of reference to corrosion and surface effects generally was an omission which Dr. Sutton treated kindly. Those were but a few of many material effects which on the whole would be more appropriate to a paper by a materials specialist.

Mr. Rotherham: There was a somewhat

curious analogy between an aircraft structure and the internal structure of metals in respect of fatigue, and it was interesting to have this developed further by Mr. Rotherham. Whether this analogy could be made more use of than at present seemed doubtful. Though there were points of similarity, it was the differences which were important. Stress concentrations, for example, might occur on different scales in materials, in structural elements and in complete structures. The apparent similarity was sometimes confusing, and misunderstandings had arisen through it not having always been clear, both in the paper and in the subsequent discussion, which kind of stress concentration had been meant at any particular stage.

The question of structural damping appeared to be of wide interest since others had also mentioned it directly to him. The point at issue was whether it might not be worth while sacrificing some degree of fatigue resistance to given loads in order to damp down vibration and so reduce the loads occurring. In some branches of general engineering this consideration appeared to be important, and favoured riveted or bolted joints as compared with more direct connections such as were obtained by welding and gluing.

The aircraft structure appeared to be different from many other types of structure, in respect of damping. In the first place, for the size of power units it carried, the aircraft structure was extremely light and its damping capacity was small. In the second place, there were ordinarily present aerodynamic damping forces which by comparison were large, often of a different order of magnitude to structural damping. The aerodynamic forces, it was true, might under critical conditions reverse so as to become a source of excitation giving rise to incipient flutter, but in such cases the effect of structural damping was secondary.

Thus, in general, structural damping on an aircraft was not of great value in resisting vibration, and such increases in damping as could be obtained by special attention in structural design were for all practical purposes negligible. Hence in the design of aircraft structures they could concentrate on fatigue resistance without the complication of damping as an additional factor.

INDUSTRIAL WIND TUNNELS

by

D. L. ELLIS, B.Sc., A.R.T.C., F.R.Ae.S.

SUMMARY

THE PAPER discusses the application of wind tunnels to aircraft design and consideration is given to the potentialities and limitations of types designed specifically for industrial use. Arguments affecting the choice of type, size and speed are stated and a detailed description is given of a particular tunnel which has very steady and even flow with a reasonable turbulence level. This description covers the aerodynamic and engineering design, the electrical driving arrangements and the six-component automatic balance.

A description is also given of a new type of high speed tunnel which has recently been put into operation. This is of the simple straight-through type and is driven by a jet engine acting as an ejector pump; the exhaust heat is used to control humidity and prevent condensation in the working section. This tunnel reaches a Mach No. of 0.9 when empty, and over 0.85 with a model in place. The Reynolds No. is 1.6 x 10^6 for a three-dimensional half model and 5 x 10^6 for two-dimensional wings.

INTRODUCTION

Before discussing the design of wind tunnels for aircraft firms it would be well to give some thought to the potentialities and limitations of tunnels in general. Several years ago the Industry in Great Britain fell into two opposed groups, one favouring the use of tunnels and operating their own, and the others almost despising them. In the more recent past the unbelievers found that some tunnel work was essential and this was done for them by the official establishments —to the detriment of their programmes of basic research. To-day it is generally accepted that a tunnel is an essential tool in developing a good design, and in addition to the firms' tunnels already existing, a number of new low and high speed tunnels have been, or are being, built.

The most useful all-round tunnel is one having a working section between 50 and 100 ft.^{2} and a speed of 200 to 300 ft./sec. This gives a Reynolds Number high enough for reliable stability measurements and allows the model to be a convenient size, large enough for accuracy, but not awkward to handle. The most valuable application of such a tunnel is in determining stability and control characteristics. Longitudinal and lateral static stability can be measured together with effectiveness of controls, optimum tailplane setting and position, change of trim with flaps, and ground effect. An accurate knowledge of these greatly reduces the anxiety which attends a first flight.

Lift slopes and increments due to flaps are given reliably, but stalling characteristics and maximum lift figures should be treated with great caution: it is only in tunnels far beyond the means of private firms (by British standards) that these can be measured with certainty. In the same way the absolute value of overall drag should not be accepted, but the relative drag of different configurations can be. A typical example is the determination of the optimum wing-nacelle combination to accommodate a given engine, cooling system and undercarriage. It is not uncommon for a firm to test a dozen or more arrangements before completing the design and in awkward cases the final drag may be half that of the original configuration. In such work the programme develops as the results are produced, and it can only be done in firms' own tunnels.

The above work requires a six-component balance reading lift, drag and cross-wind forces, and rolling, pitching and yawing moments.

Pressure plotting, or the measurement of local pressures over the surface of the model is a less spectacular, but valuable, function of a tunnel. The equipment consists only of pressure tubes let into the model and a

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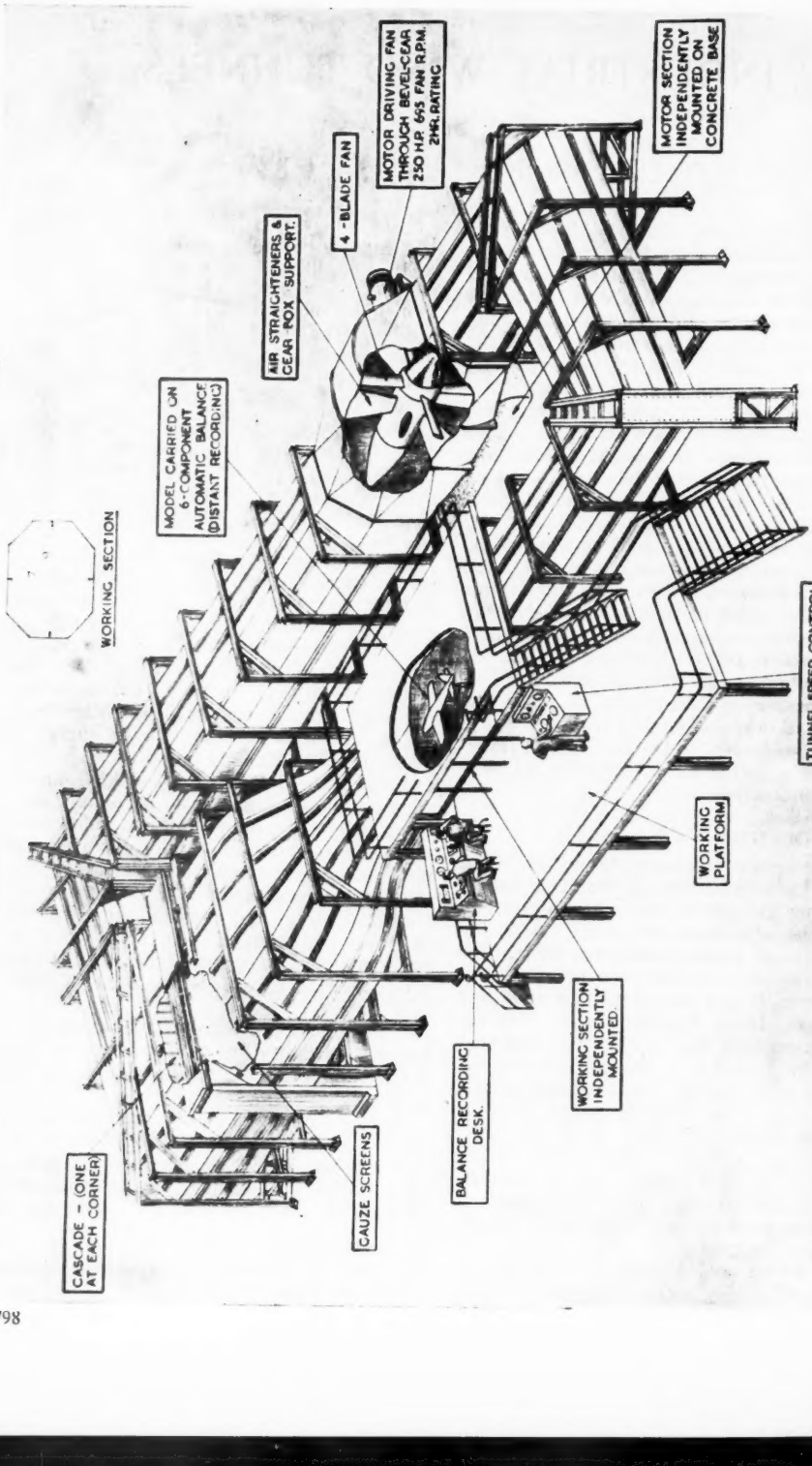

WORKING SECTION
MODEL CARRIED ON 6-COMPONENT AUTOMATIC BALANCE (DISTANT RECORDING)
AIR STRAIGHTENERS & GEAR BOX SUPPORT.
4 - BLADE FAN
MOTOR DRIVING FAN THROUGH BEVEL-GEAR 250 H.P. 665 FAN R.P.M. 2 HR. RATING
MOTOR SECTION INDEPENDENTLY MOUNTED ON CONCRETE BASE
TUNNEL SPEED CONTROL
WORKING PLATFORM
WORKING SECTION INDEPENDENTLY MOUNTED
BALANCE RECORDING DESK.
CAUZE SCREENS
CASCADE - ONE AT EACH CORNER

Fig. 1.
Pictorial view of 9 ft. × 7 ft. tunnel.

simple manometer. As long as no general or local stalling occurs, such measurements are scarcely affected by scale, so the model need only be large enough to be made accurately and the tunnel fast enough to give readable pressures.

The original function of pressure plotting was to determine the loading on such things as undercarriage doors, canopies, attachments and the like and it enables weight to be saved without danger of local failure. In recent years there has been an important extension of its scope in predicting premature shock stalling at high speed and in indicating the steps necessary to prevent it. This also can be done in a very modest tunnel, as the conversion to high speed is known accurately.

Although a low speed tunnel of reasonable size can cope with most of the aerodynamic problems of an aeroplane up to its critical speed, and can ensure that the critical is sufficiently high, it cannot indicate the behaviour beyond this speed; for this a high speed tunnel capable of the same speed as the aeroplane is required, and the technique is quite different.

Fig. 1. Pictorial view of 9 ft. x 7 ft. tunnel.

It is interesting to note that the higher the design speed of the aeroplane, the more important does low speed tunnel work become. This is because the stage has been reached where high speed is obtained by means of sweepback of the wing, and this in turn increases enormously the problems of low speed stability and control.

Visualisation of flow is often of value, particularly in examining the flow over swept-back wings. This can be achieved by attaching threads of silk or wool to the model or by introducing filaments of smoke into the air stream. The latter method is of little use, except for instructional purposes, because the smoke is only visible at speeds so low that the Reynolds number is much too low for accuracy. A better method is to use a water tunnel and, although this technique has not yet been applied to any extent to aircraft work in Great Britain, it has been widely used in Germany. The water tunnel is similar in principle to a closed wind tunnel but is much smaller (Fig. 17). The flow is made visible by means of a strong light projected through the working section and illuminating finely ground particles of Perspex or the like suspended in the stream. These appear as vivid streaks indicating the direction of flow. If the pressure at the vent of the tunnel is lowered, cavitation will occur on the model where shock waves would form in flight. Such a tunnel is of considerable value in developing, among other things, wing entries and ducts for jet engines.

TYPE AND SIZE OF TUNNEL

For low speed work the closed return circuit tunnel is now the accepted type, as it requires the least power for a given speed and size and sufficient knowledge exists to design it to an adequate standard of even and turbulence-free flow.

The choice of speed and size is a compromise. For reliability of results they should be as great as possible and as a low limit they should give a Reynolds Number, based on the mean chord of the wing, of not less than 1.5×10^6. A 9 ft. x 7 ft. tunnel at 200 ft./sec. gives this with a wing of moderate aspect ratio. The speed should not greatly exceed 300 ft./sec.; if it does spurious compressibility effects will be present at high incidences, and deflection of the model will become troublesome. In addition, speed is the more expensive variable; the power required for a given design of tunnel is directly proportional to the area of the working section but it increases as the cube of the speed. As a yardstick the 9 ft. x 7 ft. tunnel described in this paper requires 250 h.p. for a speed of just under 200 ft./sec. If the speed were increased to 300 ft./sec. the power would be 850 h.p. The same increase of Reynolds Number (50 per cent.) would be obtained by increasing the linear dimensions to 13.5 ft. x 10.5 ft. and the power to 560 h.p., the speed remaining at 200 ft./sec.

The final choice of size will generally be determined by considerations other than aerodynamic, such as cost, site and power supplies available, and the type of aircraft in which the firm specialises. Designs which have been considered for industrial use vary from 8 ft. x 6 ft. to 16 ft. x 12 ft. Towards the end of the war a committee of the S.B.A.C. recommended 13 ft. x 9 ft. at 300 ft./sec. as a suitable type; the motor was 1250 h.p. In the days of retrenchment following the war this proved to be too expensive for most firms, and plans for the construction of these tunnels fell into abeyance for the time being. Present ideas are generally more modest.

If a firm is concerned mainly with, say, high speed jet aircraft, it need not have a very large low speed tunnel, especially if it

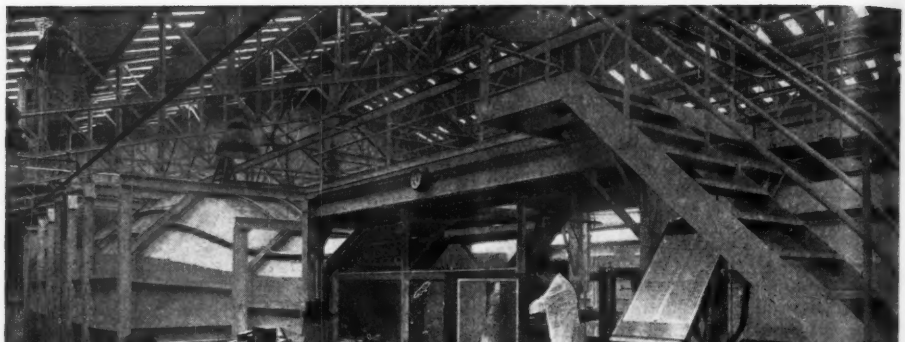


Fig. 2.
View showing working section and balance recording desk. The struts attached to the roof of the tunnel are dummies.

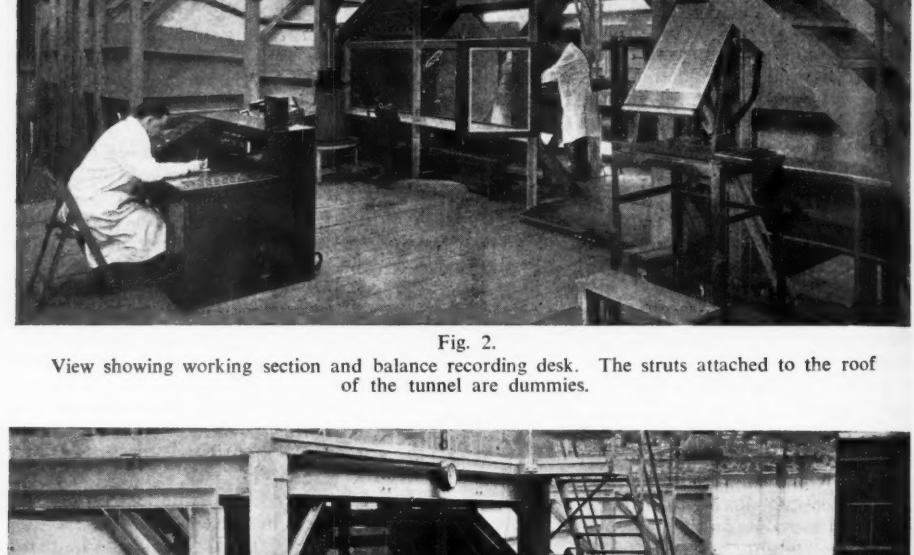


Fig. 3.
View of platform showing balance desk, control desk and Betz type manometer.

also has a high speed tunnel. Such aircraft designs tend to have a low aspect ratio, giving a high Reynolds Number for a given because the jets will certainly be arranged to span. No internal motors are required clear the tailplane, if any, and so need not be represented; entry effects can be simulated by allowing air to flow through ducts in the model.

A tunnel 8 ft. x 6 ft. is too small on practical grounds, but 9 ft. x 7 ft. or slightly larger at, say, 250 ft./sec. is very well suited to such work. The model is a comfortable size for handling and manufacture, and—an important point—is mounted at a convenient height in the tunnel for work on modifications and adjustments. On the other hand such a tunnel is too small for work on large multi-engined propeller-driven aircraft, especially of high aspect ratio. For such work it is essential to represent slipstream effects with propellers driven by motors inside the model. This can only be accomplished at a reasonable Reynolds Number with a large model at a moderate wind speed, and a correspondingly large tunnel is required.

9 FT. x 7 FT. TUNNEL

This tunnel is described in some detail as it is thought to be a suitable type for industrial use. The tunnel and its associated balance and electrical equipment were designed and constructed by the English Electric Co. for its Aircraft Division; the aerodynamic design was based on work done by Vickers-Armstrongs Ltd., Weybridge, and on recommendations of the Society of British Aircraft Constructors' Wind Tunnel Committee.

It was decided to build the tunnel in steel partly because the firm had facilities for heavy fabrication work and partly because in 1945, when the design was put in hand, steel was not quite so difficult to obtain as were concrete and timber. The decision has not been regretted as the tunnel has proved to be entirely satisfactory.

Aerodynamic design

The aim of the basic design was to achieve a high standard of steadiness and evenness of flow with moderately low turbulence in a reasonable overall size. Steadiness is important because *ad hoc* work is frequently concerned with small differences; on the other hand, work at extremely low turbulence is normally the province of the official establishments and the high cost of providing it is hardly justified in an industrial tunnel.

The salient points of the design are:

Contraction ratio 5:1
Max. diffuser angle in any plane 5°
No expansion in 1st and 2nd corners.
10 per cent. expansion and Salter type vanes in 3rd and 4th corners.
Settling length 20 ft.
Constant net area through fan section.
Working section length 18 ft.
Provision for screens in settling length.

The shape of the contraction was based on recent work of Lilley and others and it is rather longer than usual. The combination of this with the settling length and the long working section have resulted in a relatively high speed at the first corner, where some 33 per cent. of the losses occur and the power factor therefore is not good. This means that the power required is perhaps 50 h.p. greater than it could have been, but this is a small price to pay for the improvement in flow.

Performance

With no screens in place (there is no honeycomb) the maximum speed at 250 h.p. was just 200 ft./sec. Soot marks on the first corner vanes indicated some separation behind ridges near the leading edges, due to swelling of the wooden noses. When these have been rubbed down it is expected that there will be a small gain in speed. The velocity distribution varied $\pm$ 1½ per cent., although in way of the model it was $\pm$ ½ per cent. A surprising feature was a high spot of + 1½ per cent. near the inner wall and above the centre line; if anything, a low spot would be expected here and it is clear that there can be no serious separation in the return circuit. This is attributed mainly to the diffuser angle being not more than 5°. Also, there is no trace of a shadow from the fan nacelle.

One screen was then fitted and this is the condition in which the tunnel is now running as it has not been found necessary to fit the second. The screen is of 2q resistance, 30 mesh 31 S.W.G. stainless steel and the speed is now 187 ft./sec.; the velocity distribution varies less than $\pm$ 0.3 per cent. which was the limit of accuracy of the equipment used. Random fluctuations of the mean velocity are within $\pm$ 0.1 per cent. with the tunnel

Fig. 4.
Fan section and driving motor.

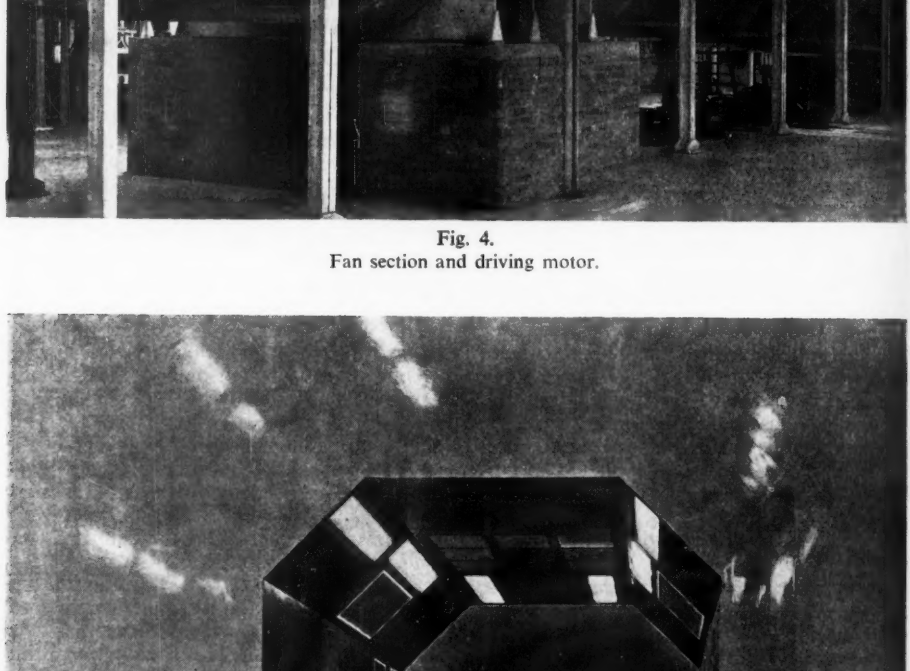


Fig. 5.
Contraction and working section.

empty, and with an unstalled complete model of 6 ft. span; when the model stalls this figure increases to ± 0.3 per cent. Once the temperatures of the tunnel and the electric drive are steady, the mean speed maintains itself without automatic control within these limits almost indefinitely. It varies as the incidence of the model is changed, so that automatic control is still desirable. It will be appreciated that the design of the electrical equipment is a contributory factor to this steadiness.

An assessment of turbulence was made by studying the behaviour of a two-dimensional wing, using the china clay method and measurement of the wake drag to indicate transition. The wing was 4 ft. 6 in. chord and extended from the floor to the roof of the tunnel. The section was the symmetrical ECL 1240 and at 0° incidence the pressure distribution curve is flat-topped back to 50 per cent. so that transition should occur just behind this point in turbulence free flow. One would not expect this to be achieved with no smoothing arrangements and, without the screen in place, transition varied from 45 per cent. at $R = 2.6 \times 10^6$ to 22 per cent. at $R = 4.9 \times 10^6$. With one screen, however, the transition point was maintained behind 50 per cent. up to $R = 4 \times 10^6$ (150 ft./sec.). There was no sudden collapse beyond this point and transition was still at 41 per cent. at top speed. Fig. 6 shows transition at 57 per cent. indicated by the china clay method.

No accurate calibration has yet been made of directional distribution, but the behaviour of a complete model during the measurement of lateral derivatives indicates that there can be no serious errors from this cause.

Construction

A general impression of the construction may be obtained from Figs. 1-4 while Fig. 7 gives the general arrangement of the circuit. This was built in 32 sections including the working section, the cascades and the fan section. The length of the sections was determined by the length of plate available (12 ft. maximum) and transport; the completed units had to be moved 9 miles by road to the final site. Except at the motor section the plates are $\frac{3}{8}$ in. throughout, the main frames are 6 in. x $3\frac{1}{2}$ in. or 8 in. x $3\frac{1}{2}$ in. channels and the stiffeners are 3 in. x 3 in. or 4 in. x 3 in. R.S. joists. The stiffeners are nowhere more than 3 ft. apart and, as well as preventing drumming, they serve to control the contour of the contraction. The total weight of steel is 225 tons and the structure is carried on 140 pads; these are not bolted to the foundation except at the screen section.

A typical section is shown in Fig. 8; it is welded throughout, bolts being used only to make the joints between adjacent sections. The shape is controlled at each end by diaphragms fabricated from $\frac{1}{2}$ in. plate 9 in. wide, the mitres being machined before assembly. The main plates are flame cut and rough ground along their lengthwise edges, but the ends are machined to form a good joint. The sections were made in sequence working downstream from the working section, and the downstream face of each was used as a jig for the upstream face of the next.

The method of making the joints is also shown in Fig. 8. The end frames are pulled together by $\frac{3}{4}$ in. bolts at approximately one foot centres until the diaphragms butt on hardwood strips placed between them; at the same time a strip of lead is squeezed between the ends of the main plates, and the thickness of the hardwood is such that about $\frac{1}{8}$ in. of lead is left in the joint when the bolts are tight. The inner face is scraped flush.

Working section

This is isolated from the circuit by the breathing gap downstream and a sliding joint at the end of the contraction. As it turns out this joint could have been eliminated because the vibration, which is nowhere severe, is least in the contraction structure.

The walls of the working section are mahogany panels or Perspex windows carried in a steel framework. The vertical panels are detachable and interchangeable so that any combination of solid panels and windows may be fitted. A turntable in the floor can be operated by hand from the platform or by the balance when this is in operation, and a pneumatic brake holds it in any desired position. A system of interlocks and microswitches prevents the yawing motor of the balance from operating, unless the brake is off and the hand drive de-clutched. Individually-switched fluorescent lights are flush-mounted in the mitres.

Fan section

The fan section (Figs. 4, 9) is again of welded construction. The main drum is of

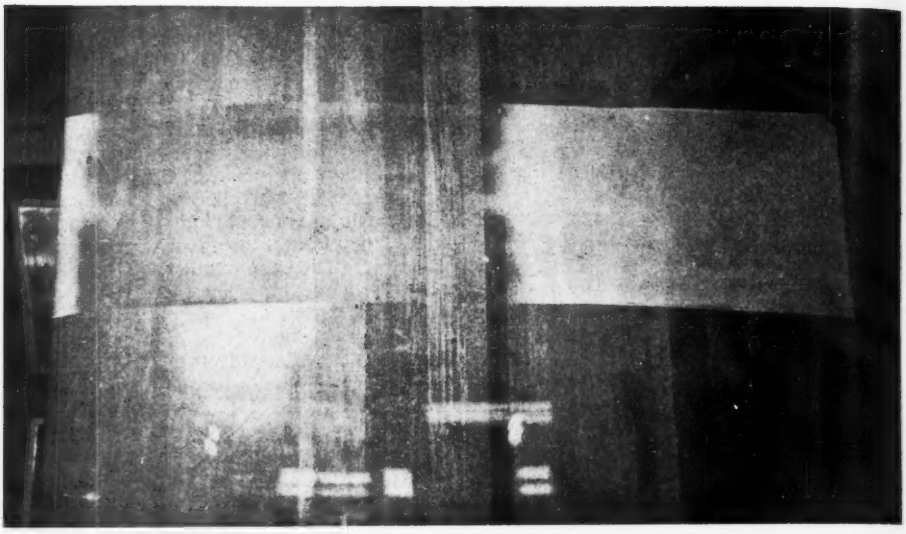


Fig. 6.
Two-dimensional wing section with china clay indicating transition at 57 per cent. at Reynolds number $= 4 \times 10^6$.

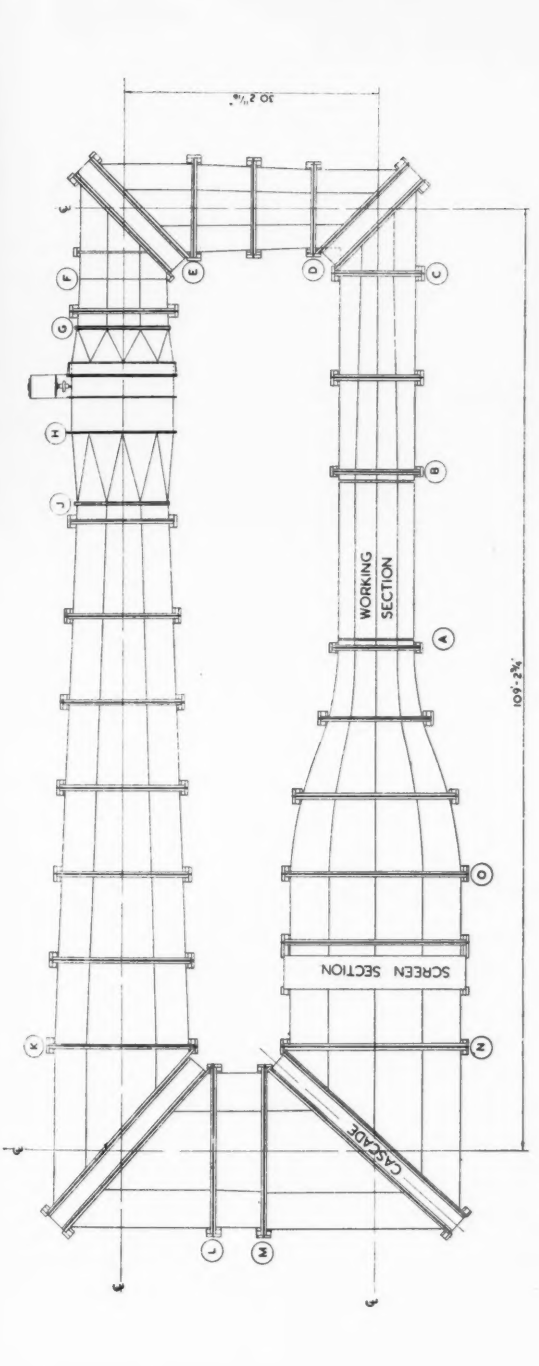
$\frac{1}{2}$ in. plate with three diaphragms of one inch plate and the external bracket for the motor is welded to two of these diaphragms. The drive to the fan is taken through one of the nacelle supports to a David Brown bevel reduction box and this allows an industrial motor of standard construction to be used, running at 1500 r.p.m. The combined cost of this motor and gear box is less than the cost of the larger motor that would have been required to drive the fan direct at 695 r.p.m. A safety trap filled with balsa reduces danger to the fan from small articles left in the tunnel.

The six supports for the nacelle are of composite construction. The structural parts are welded flat steel plate and these are faired by elliptical nose sections and circular arc tails of wood. The cost of these is a small fraction of that of fully developed aerofoil sections and it is certain that they have no adverse effect of any significance on the tunnel performance.

Efficient fan design requires a hub or blanking of not less than 0.3 of the fan diameter, and this hub must be faired by means of a rounded nose and a tail, one or other of which serves to house the drive; in this case the gear box is carried behind the fan in a cylinder the rear of which is faired by a light spinning. It is sometimes argued that expensive construction is required to maintain constant area past the fan section, but this is not necessarily so. In general, low speed atmospheric tunnels have sections of four or eight flat surfaces so that transition sections are required before and after the fan. In this tunnel these vary from a regular octagon to a circle and they are fabricated from alternate flat and curved triangular plates of $\frac{1}{8}$ in. steel. The net area at the fan is the same as that at the beginning and end of the transition sections, and the nose and tail fairings are proportioned to maintain this area at all stations. This arrangement is no more complicated than one giving constant gross area, and it removes the danger of separation over the tail of the nacelle.

Corner cascades

The first and second corners (Fig. 11) are of the Collar type with no expansion. The surfaces are of 16 gauge steel spot-welded together at the tails and to a channel at the nose. The form is maintained by a wood skeleton and the nose is a hardwood fairing. The third and fourth corners (Fig. 12) have an expansion of 10 per cent. and are fitted with single surface vanes at $\frac{1}{3}$ chord spacing.



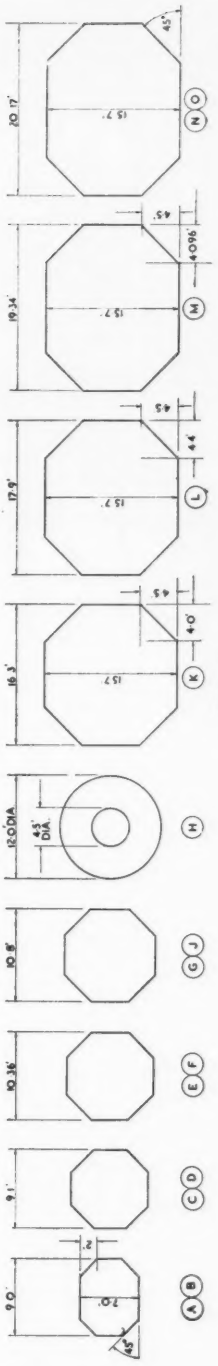
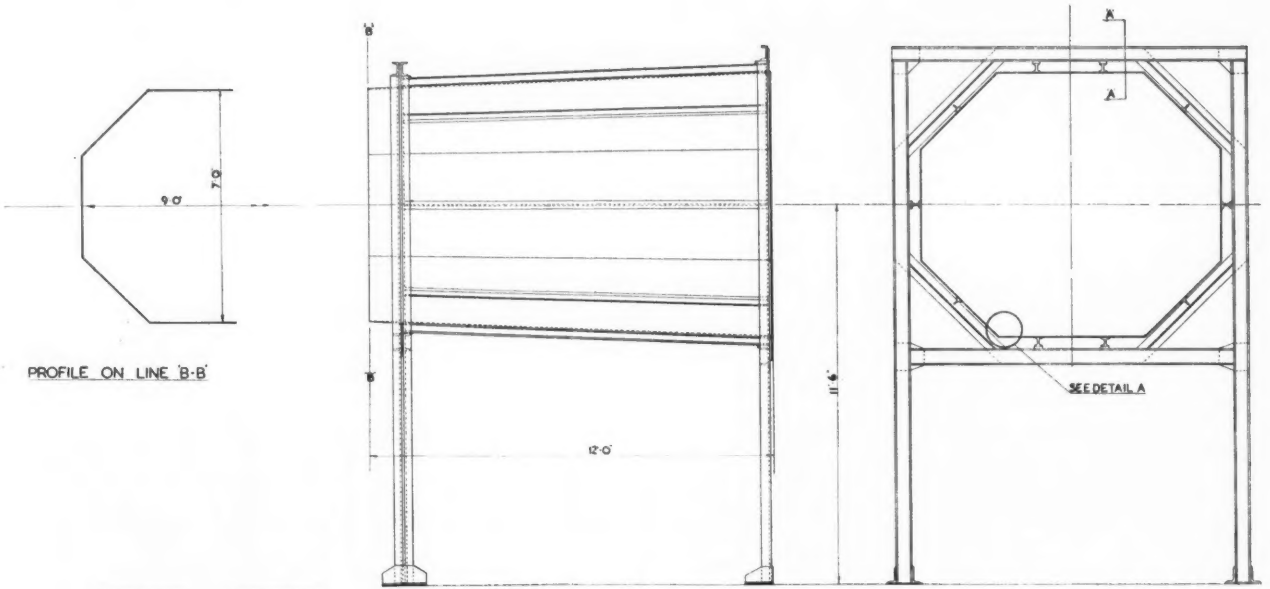
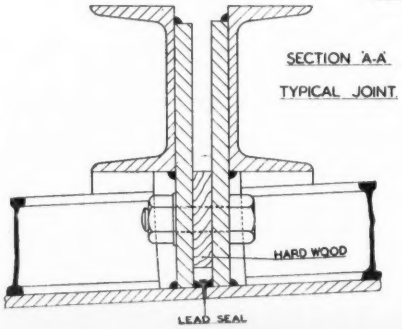


Fig. 7.
General arrangement of tunnel.


9'0"
7'0"
PROFILE ON LINE 'B-B'
8"
8"
12'0"
11'6"
A
A
SEE DETAIL A


SECTION 'A-A'
TYPICAL JOINT
HARD WOOD
LEAD SEAL

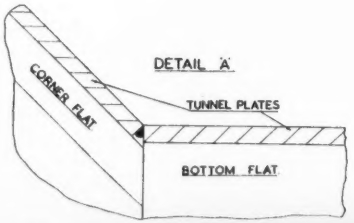

DETAIL 'A'
CORNER FLAT
TUNNEL PLATES
BOTTOM FLAT

Fig. 8.

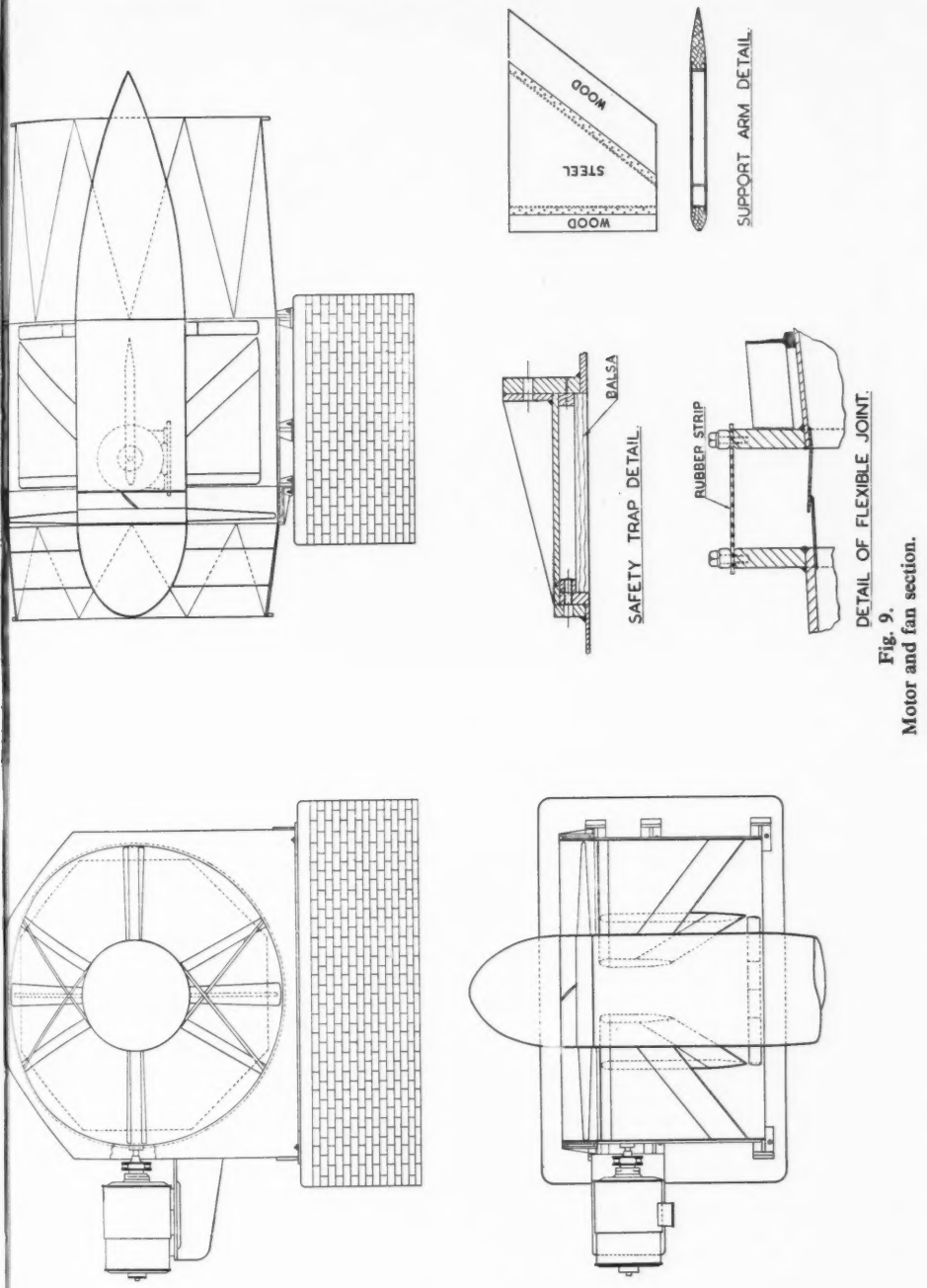


Fig. 9.
Motor and fan section.

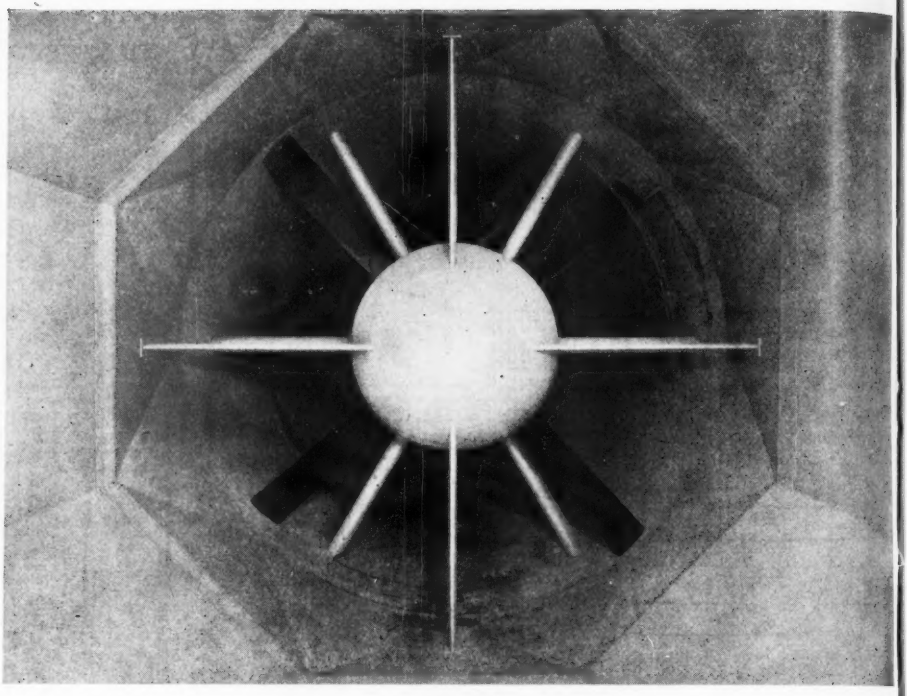


Fig. 10.
Fan section.

No attempt is made to seal individual vanes; each cascade is mounted in an airtight box.

Screen Section

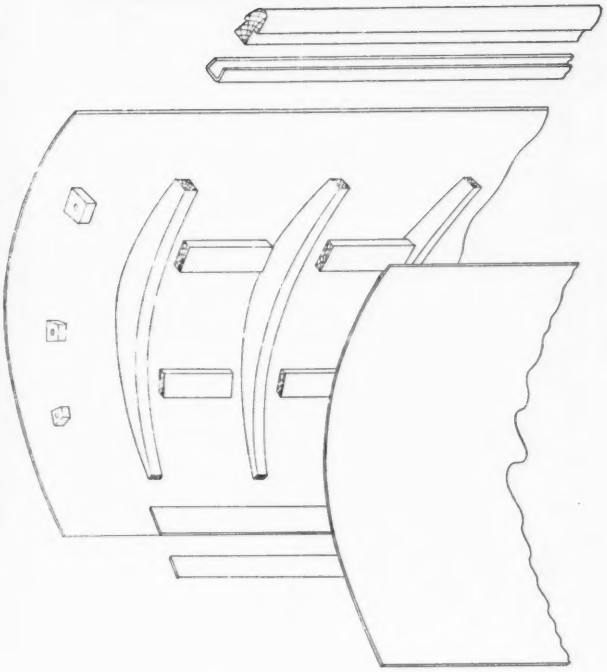
This is shown in Fig. 13 and, like the corners, is a rectangular airtight box. The screen is not trimmed to fit the mitres, and is clamped at the top and bottom edges only. The mitres are wood panels with clearance slots for the screen.

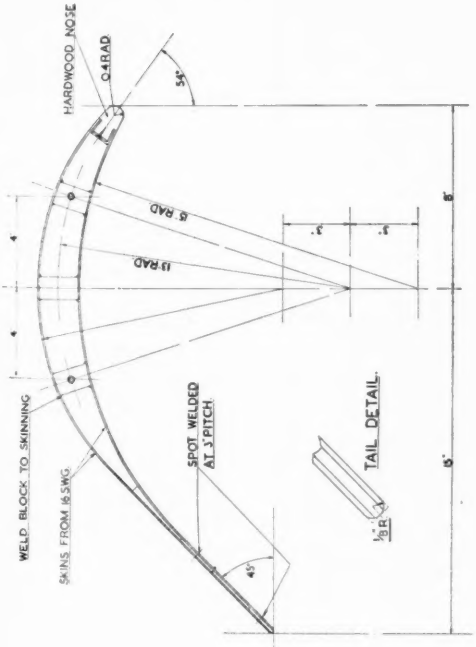
Drive and Control

The design of a satisfactory wind tunnel drive sets a number of unusual problems for the electrical engineer because an exceptionally high standard of steadiness and stability may be required over a speed range of up to 10:1, which corresponds to a power range of 1,000:1. There is no doubt that except for the largest sizes the Ward-Leonard system is the most satisfactory solution; it has the necessary flexibility, it is easily adaptable to various means of hand or automatic control and, if the motor is an A.C. machine, it is unaffected by line voltage fluctuations.

The motor for this tunnel has a normal rating of 200 h.p. with a two hour over-load of 250 h.p. and it is supplied from a 315 h.p. synchronous motor-generator set. The arrangement adopted for supplying the generator field was determined by the requirements of automatic control from a manometer operated by the tunnel pressure, and having an accuracy of 0.15 per cent. of top speed. A fully electronic system was designed to meet this requirement and was eventually developed to be sensitive to less than 0.1 per cent.

Automatic operation depends on a capacity bridge of which one arm is varied by a rising float manometer. The float carries the moving plates of a tubular condenser which balances the capacity set on a calibrated manual condenser in the other arm of the bridge. Manual operation is by coarse and fine potentiometers operating through the same system.





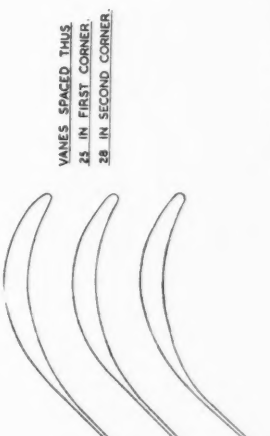
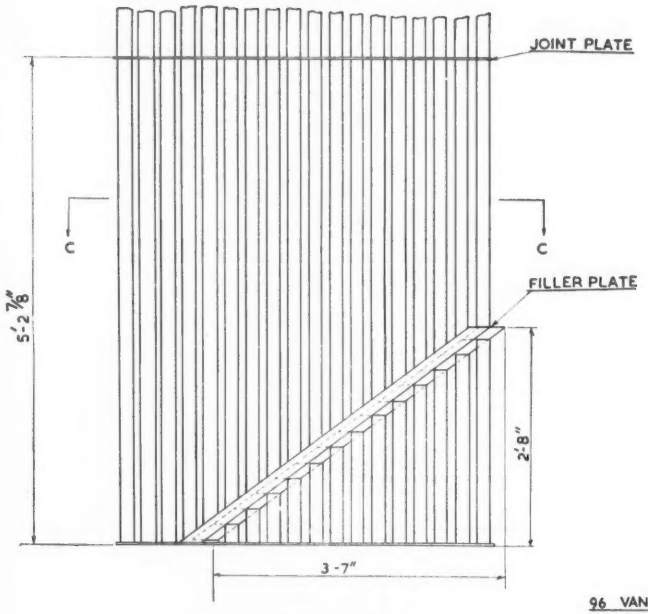


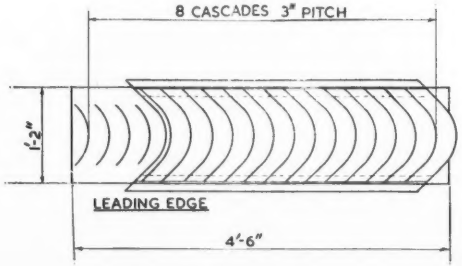
Fig. 11.
Cascade detail: first and second corners.



SECTION THROUGH JOINT PLATE.

96 VANES IN 3RD CORNER.

108 VANES IN 4TH CORNER.

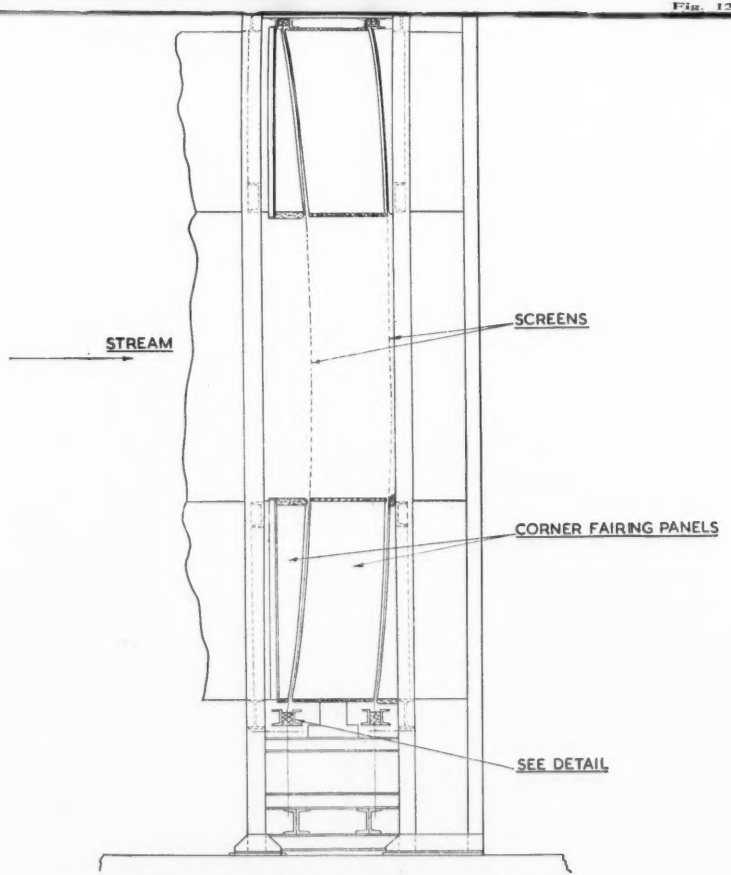


SECTION ON 'C-C'

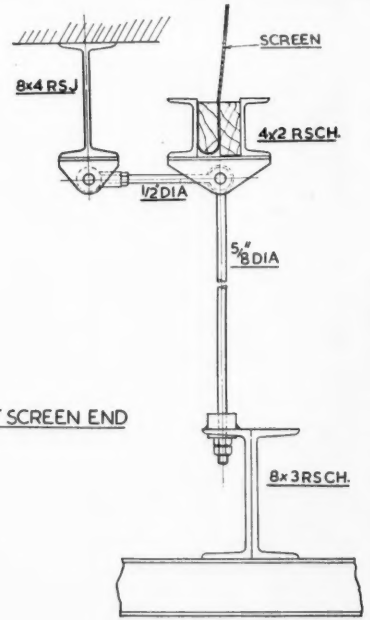
Fig. 12.

SECTION ON 'C-C'

Fig. 12.



VIEW OF SCREEN SECTION WITH AIRTIGHT SIDE PANELS REMOVED.



DETAIL OF SCREEN END FIXING.

Fig. 13.
Detail of screen section.

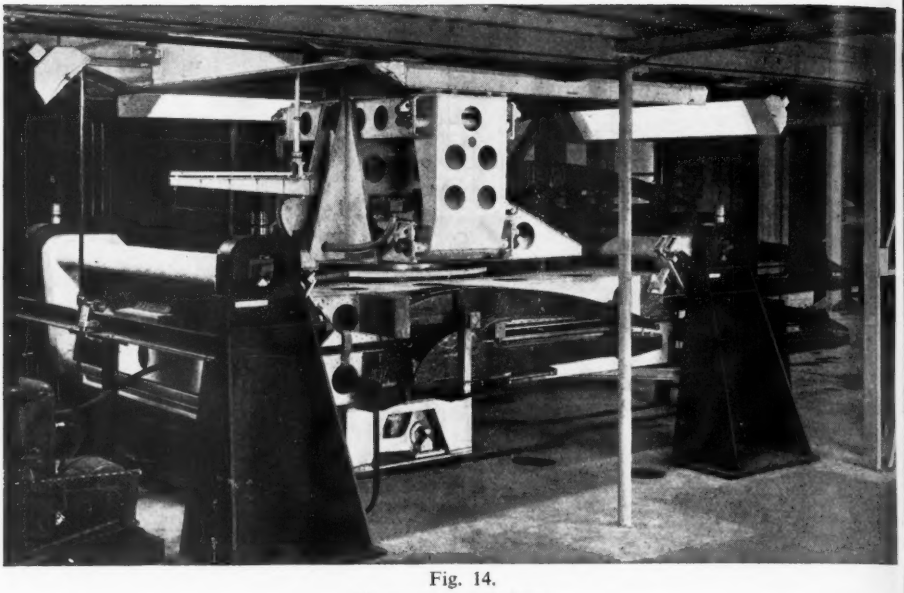


Fig. 14.
Six-component balance.

The power for the generator field comes from two Thyratrons arranged as a full wave rectifier and their output is determined by a signal voltage fed to their grids from the manual or automatic controls which in turn take it from a stabilised D.C. supply. A current limiting device in the armature circuit feeds another signal to the grids of the Thyratrons and during acceleration or deceleration this limits the motor torque to 130 per cent. of full load and this value cannot be increased by rough handling of the controls. Normal shut down by the stop button is accomplished by reduction of the generator voltage and is accompanied by regenerative braking, the braking torque being limited to 130 per cent. of full load.

Balance Gear

There is more diversity of strongly held opinion on balance design than there is on anything else to do with wind tunnels, and the writer must confess to being as biased as anyone. There are a few points on which there is general agreement and among them is the acceptance that wire suspension, knife edges and manually-operated steelyards are not suitable for modern conditions. Rigid model supports are now used and linkages are swung on single or crossed spring flexures and pivots which are very robust and require no maintenance. The manual steelyard has given place to the Kelvin current balance or the self-balancing steelyard. The Kelvin balance has three co-axial coils, the middle one moving under the influence of the applied force. An inductive pick-up indicates this movement and the operator varies a D.C. current in the coils until balance is restored. The value of the current, indicated on a sensitive ammeter, is the measure of the force. The disadvantage of this system is that an operator is required for each component if simultaneous readings are wanted. Automatic balancing would be possible but the same result can be obtained with less complication by other means.

The self-balancing steelyard (Fig. 16) has the usual jockey weight but this is traversed by a lead screw driven by a reversible electric motor. Deflection of the free end of the beam transmits a signal to the motor which moves the jockey weight until the beam is in balance, and a Selsyn transmitter records the number of turns of the screw on a counter on the control desk. The signal to the motor may be from an inductive pick-up through an amplifier, but quite satisfactory results can be obtained with simple on-off contacts. The weighbeams

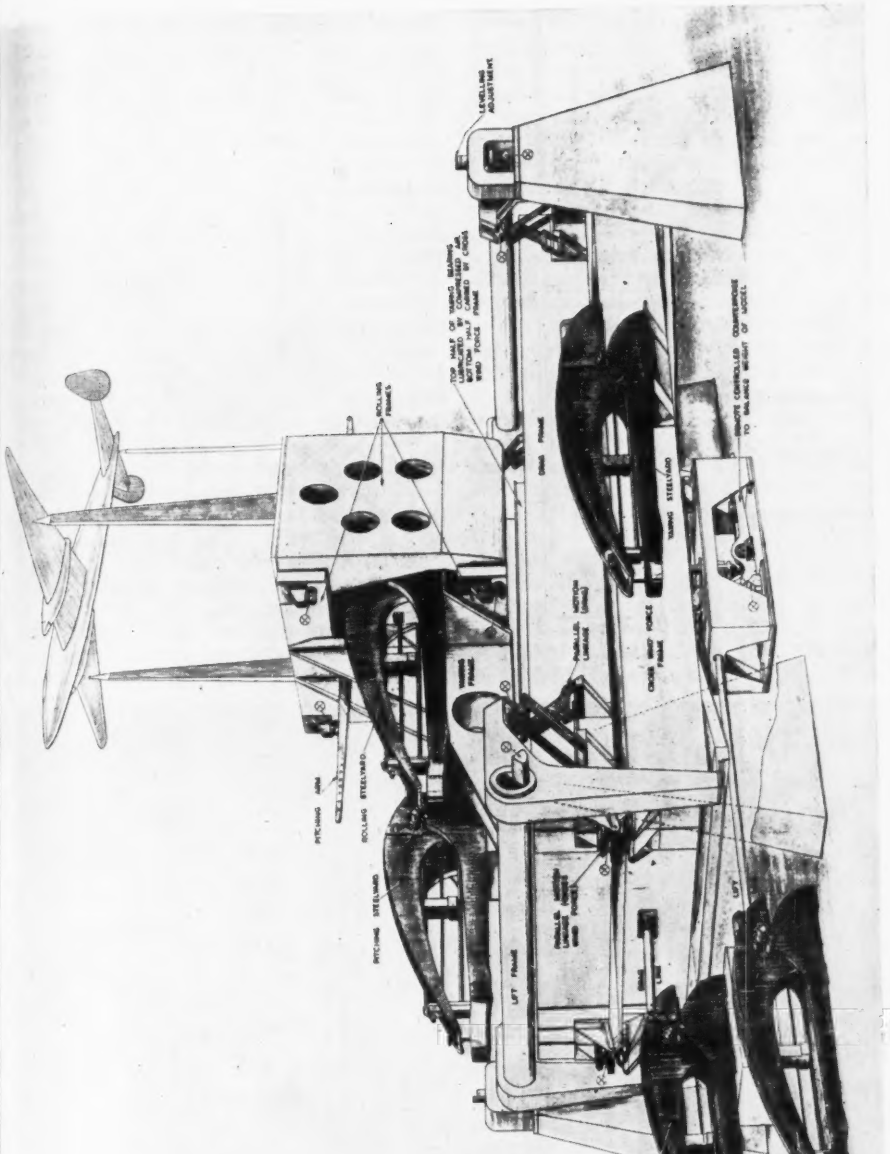


Fig. 15.
Pictorial view of balance. The crosses indicate crossed-spring pivots.

SUPPORTS AND FAIRINGS
ROLLING MOMENT PICK-UP
ROLLING FRAMES
CROSS SPRING PIVOTS
YAW PICK-UP
TOP HALF OF YAWING BEARING LUBRICATED BY COMPRESSED AIR
BOTTOM HALF CARRIED ON CROSS WIND FORCE FRAME
AXIS BEARINGS FOR YAW
PARALLEL MOTION LINKAGE (DRAG)
CROSS WIND FORCE PICK-UP
STREAM
PITCH
PITCH ADJUSTMENT
LIFT
PITCHING ARM
PITCHING MOMENT LINKAGE
DRAG FRAME
CROSS WIND FORCE FRAME
CROSS SPRING PIVOT
REMOTE CONTROLLED COUNTER POISE TO BALANCE WEIGHT OF MODEL
JOCKEY WEIGHT
MOTOR
DRAG
LIFT
PARALLEL MOTION LINKAGE (DRAG)
TYPICAL CROSS SPRING PIVOT
APPLIED FORCE
MOTOR BRAKE UNIT
SELSYN TRANSMITTER
GEARING
JOCKEY WEIGHT
CROSS SPRING PIVOT
CONTROL DESK INDICATOR
SELSYN RECEIVER
COUNTER
DIRECTION
SLIDE RAILS
MEASURING
CONTACTS
THE MOTOR BRAKE UNIT MOVES THE JOCKEY WEIGHT UNTIL BALANCE IS RESTORED. THE SELSYN TRANSMITTER COUPLED TO THE END OF THE LEAD SCREW TRANSMITS THE NUMBER OF TURNS REQUIRED TO RESTORE BALANCE.
DETAIL OF SELF BALANCING STEELYARD.

Fig. 16.

used on the 9 ft. x 7 ft. balance (Figs. 14, 15 and 16) were initially fitted with two-way contacts but these have been replaced by a single contact operating a spring-loaded relay so that the motor runs one way when the contact is made, and reverses immediately it opens. The motor, therefore, is never at rest and hunts about the mean position of balance by about one revolution. A dog clutch with nearly a revolution of backlash is introduced into the drive to the counter which thus comes to rest momentarily on either side of the mean value. A sensitivity of one in 1200 of maximum load is obtained with this arrangement. When the weigh-beam is appreciably out of balance a second contact shorts an eddy current brake and allows the motor to run faster until balance is approached.

There are at least as many linkage systems as there are people who have designed balances, but most of them fall into one of three groups. The first is the "pyramid" in which one system of links converges to an imaginary apex at the C.G. of the model. The C.G. becomes a virtual centre round which moments are measured. Another system of links allows freedom for force measurements. The advantages of this system are that any type of support may be used to carry the model, and there are no "live" pivots in the model. It is also possible to earth all the steelyards, but this is only important if they are manually operated. The main disadvantage is that errors may arise from quite small mis-alignments or deflections of the links or supports, and these errors are difficult to detect. If all the steelyards are earthed some of the components appear as sums or differences of two readings, which means additional computing and reduced accuracy.

The second group has three supports to carry the model, two to the wing and one to the tail (or nose). The supports are pivoted in the model and the forces in each are measured independently. This type is simple and robust, and even if the supports deflect appreciably the three moments are still measured about a known centre (the mid-point of the pivots in the wing). Against this, such a system cannot measure all components directly and it is prone to interference effects (lift force producing a drag reading, and so on) because it is not practicable to use parallel motion linkages. A typical balance of this type will measure pitch and cross wind force directly while

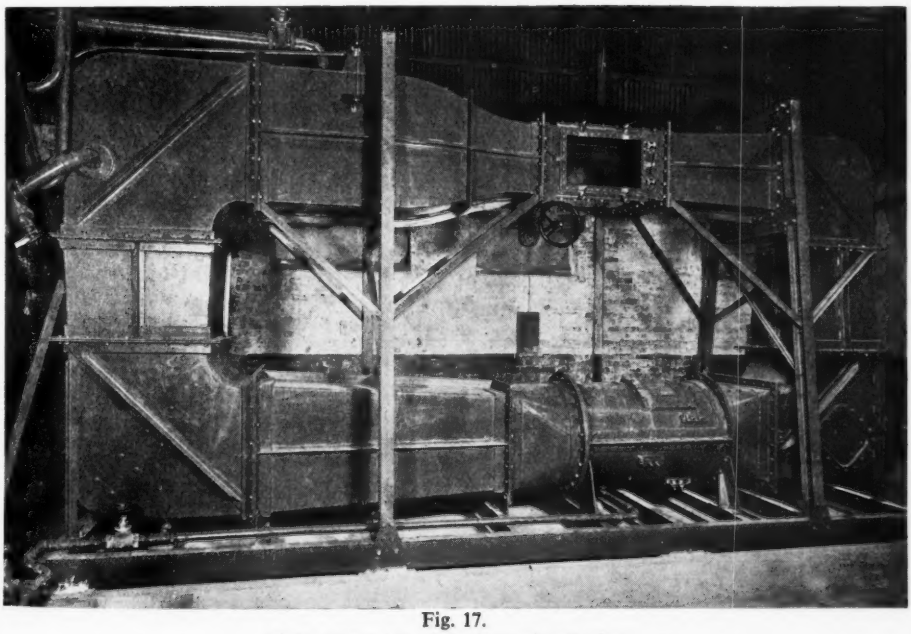


Fig. 17.
18 in. water tunnel for flow visualisation.

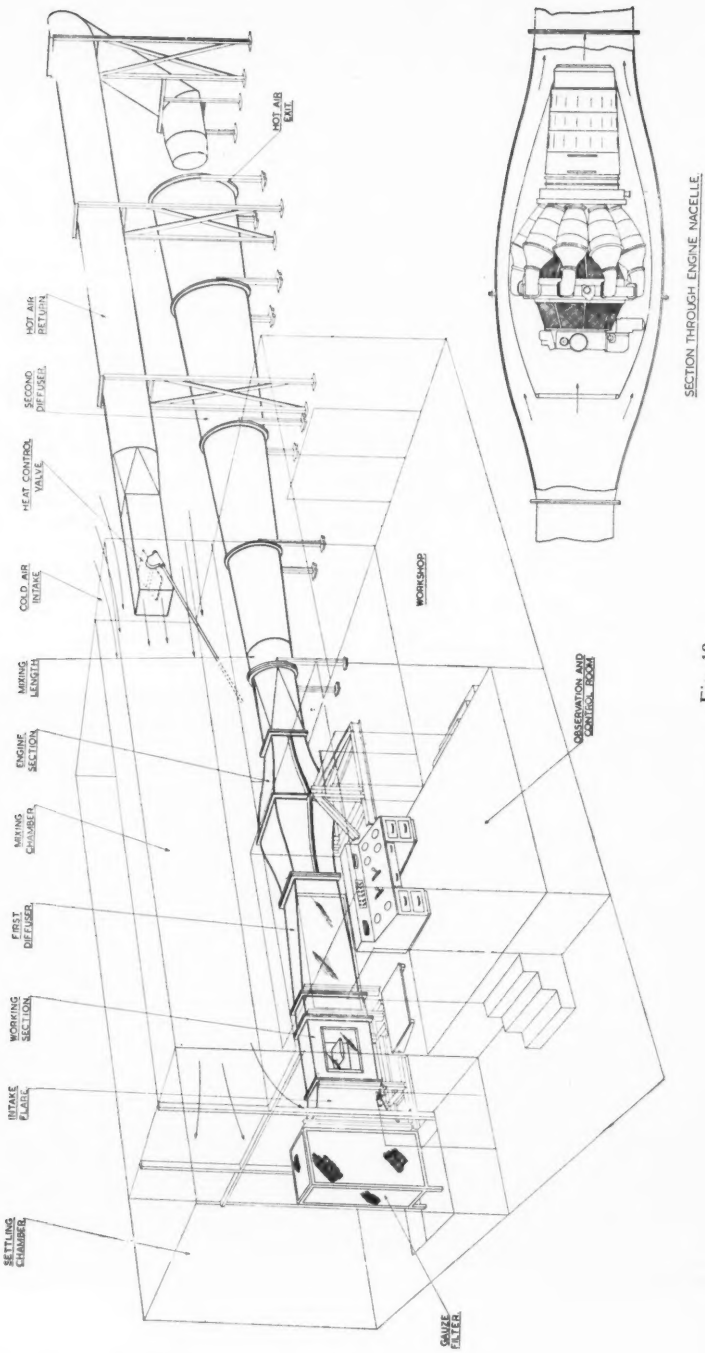


Fig. 18.
High speed wind tunnel.

lift is the sum of three readings, roll the difference of two, drag the sum of two and yaw the difference of two.

Balances of the third group also carry the model on three strut supports with gimbal pivots, and again pitching moment is measured direct from the force in the tail strut. The main supports, however, are carried by a series of frames and each frame (or frame group) is linked to the next in such a way that relative motion between them is only possible in the direction of one of the components to be measured. The inter-frame force is transmitted to a steelyard carried by one of the frames and this reads the corresponding component directly. There are many possible combinations of frame sequences and linkage systems for balances of this type but they are all based on the important principle of direct reading of all components, so that a minimum of computation is required. They are perhaps the most complicated, but not necessarily the most expensive, because they do not require such a high standard of accuracy of manufacture as the pyramid type. Parallel motion linkages are easily applied in this case and they allow even more latitude of alignment as well as eliminating inter-component interference.

9 FT. X 7 FT. BALANCE

This is a six-component automatic balance of the third type and its working principles are indicated in Figs. 15 and 16. The lift frames are two large bell cranks linked to give parallel vertical motion, and they are carried by four columns mounted on a concrete foundation raft. The pick-ups for the crossed spring pivots are adjustable vertically for final levelling and they take the load through ball thrust bearings. These bearings together with yokes and pin bearings in the third plane ensure that no twist or racking can be transmitted to the crossed springs.

The drag frame is a rectangular box swung on parallel motion links from the lift frames. A similar box swung from the drag frame on another system of links gives freedom in the cross wind direction. The linkage used for both these suspensions is the Tchebicheff (Fig. 16) which is a straight line to the 6th order; it is more compact than the Watts and can be arranged to have all flexures in tension. Racking of the springs due to deflection of the overhung brackets is prevented by suitable ball and pin bearings. The centre distances of the earthed supports and the drag and cross wind links are not in the least critical; it is only important that they should be level.

The yawing frame is supported from the cross wind frame by a compressed air bearing passing through a large clearance hole in the drag frame. The bearing is the type developed by the Royal Aircraft Establishment and has two plain thrust faces 38 in. diameter and 8 in. wide. Air under pressure is fed from a manifold cast in the lower half to an annular groove in the lower face. The air supply is through a simple flexible hose and if this is a certain critical length the air pressure produces no drag reaction. The yawing frame carries the pitching linkage and the rolling frames.

The readings from the six steelyards are transmitted to a group of counters on the left of the desk on the main platform (Fig. 2). Other counters indicate pitch and yaw settings which are controlled from the desk and signal lights indicate which circuits are live and if any steelyard reaches the end of its travel.

HIGH SPEED TUNNEL

The need for high speed tunnel facilities for industry has been felt keenly for some few years, but unfortunately the power requirements of such tunnels are prodigous; at a Mach Number of 0.9 the equivalent

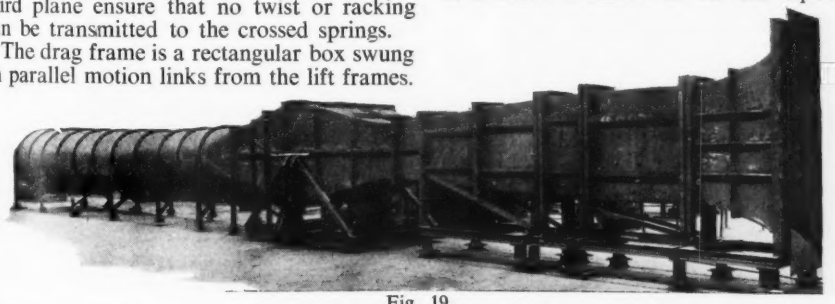


Fig .19.
Shop assembly of high speed tunnel. The working section is the second from the right and is 4 ft. × 1 ft. It was later reduced to 3 ft. 8 in. by liners.

power in the working section is nearly 1300 h.p. per square foot if the stagnation pressure is atmospheric. The input power will be about a fifth of this with good design, but even so it is still very large for a tunnel big enough to test complete models. Intermittent tunnels exist which run off stored compressed air or from vacuum tanks but these can only run for a minute or so per hour with reasonable sized compressors, and are not suitable for industrial use.

When the 9 ft. x 7 ft. tunnel was put in hand it was decided to proceed with a high speed tunnel as well, and means of driving it were investigated. Among these was the use of a jet engine acting as an ejector pump and although this would not be considered good practice for permanent plant in normal times, it was justified by the acute restrictions which applied to heavy electrical equipment, and power to drive it.

Preliminary calculations and model tests with compressed air were satisfactory and the tunnel shown in Figs. 18-20 was built. The air is drawn from the settling chamber through a contracting flare to the working section, which is 3 ft. 8 in. x 1 ft. It is then diffused until it reaches what may be called the pumping section. The engine, a Rolls Royce Nene, is housed in a nacelle carried in a bulge in the tunnel and there is an annular space between the inner nacelle and the outer wall. One third of the tunnel air is drawn direct into the engine and the remainder through the annular space by the ejector action of the jet in the long second diffuser. The tunnel reaches a Mach number of 0.9 empty, and 0.83 with a 15 in. chord wing model; the corresponding Reynolds number is 5×10^6, and the flow is steady.

A straight-through tunnel of this type would suffer from condensation troubles on most days of the year if the humidity were not lowered at the intake. This is done by collecting a part of the hot efflux and mixing it with the intake air and, although moisture is added, the overall humidity is lowered by the temperature increase.

The tunnel proper and the hot air return are welded steel construction. The working section is $\frac{1}{2}$ in. plate, the first diffuser, $\frac{3}{8}$ in., and the flare and engine section $\frac{1}{4}$ in.; the remainder is $\frac{1}{8}$ in. Upstream of the engine there are joints arranged to allow the fitting of interchangeable working sections.

The normal type of balance is not suitable for high speed tunnels because the struts cause premature choking and so limit the maximum speed. The most satisfactory method is to carry the model on a sting extending downstream from the tail, measuring the forces by strain gauges built into the model itself; jet designs lend themselves particularly well to this method and in many cases the sting can be arranged to simulate the jet interference effects.

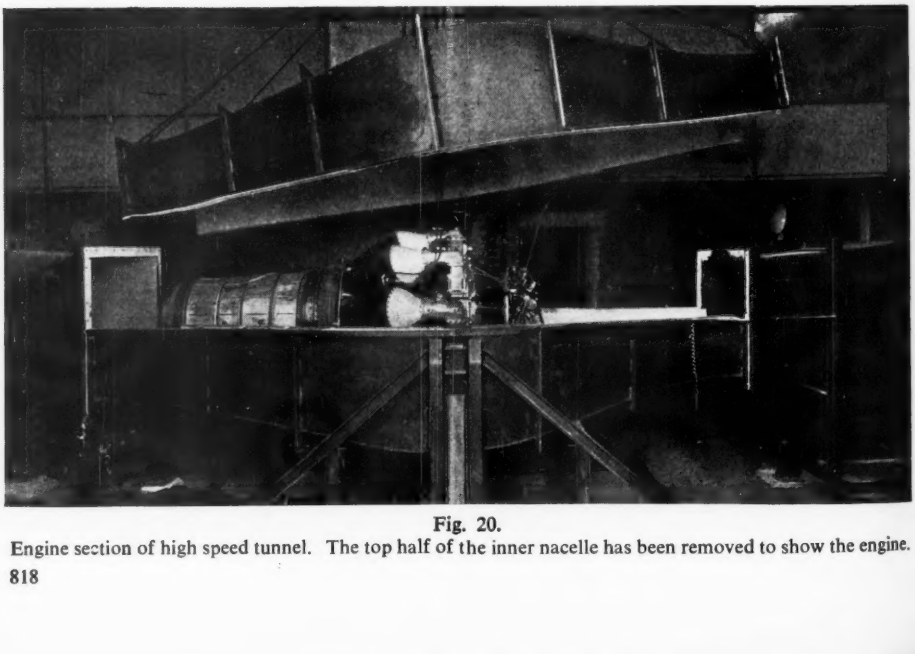


Fig. 20.

Engine section of high speed tunnel. The top half of the inner nacelle has been removed to show the engine.

THE 1949 GARDEN PARTY

THE 1949 Garden Party, marking the year in which a Charter of Incorporation was granted to the Society, was held at White Waltham aerodrome, near Maidenhead, on Sunday 8th May 1949.

The emphasis was on light aeroplanes and the types shown—and flown—ranged from the old Bleriot and Deperdussin of 1909 and well-known types of the 1930's to more modern light aeroplanes and a helicopter.

Altogether some 5,000 members and their guests were present, many of whom arrived by air.

The highlight of an afternoon in which many light aircraft demonstrated their capabilities was the ascent in a 12,000 cu. ft. hydrogen balloon by the President, Dr. H. Roxbee Cox, piloted by M. Charles Dollfus. The balloon, released at six o'clock from the aerodrome, made a cross-country flight of five miles, landing at Foliejon Park, Winkfield, after a flight of twenty-two minutes.

During the afternoon a selection of music was played by the Fairey Aviation Works' Band. The music included a " March for the Flight of Mr. Lunardi's Air Balloon " composed by Samuel Wesley (probably about 1784), a copy of which was found in the Hodgson-Cuthbert Collection and orchestrated specially for the Fairey Aviation Works' Band by Dr. Denis Wright.

White Waltham aerodrome was kindly lent for the occasion by the Ministry of Supply and the Fairey Aviation Co. Ltd. and to them the Council pay a warm tribute.

The Society is particularly indebted to Sir Richard Fairey, past President of the Society, and to the Directors and Staff of the Fairey Aviation Co. Ltd. for their assistance in the general organisation of the Garden Party, especially Group Captain G. R. Slade, Chief Test Pilot, Lt. Commander B. J. Hurren, Sales Development Manager of the Company, and Major S. V. Sippe.

Group Captain Slade was Officer Commanding Flying and the Council wish to pay special tribute to him and his assistants for their work in connection with the Flying programme. The Council also wish to thank the Ministries of Supply and Civil Aviation, the Air Ministry, Mr. V. Robb, Senior Air Traffic Control officer at White Waltham, and his assistants and the London Air Traffic Control Organisation.

The President, Dr. H. Roxbee Cox, D.I.C., B.Sc., F.R.Ae.S., F.I.Ae.S., and Mrs. Roxbee Cox receiving guests at White Waltham.

The co-operation of the West London Aero Club and the Reserve Command, Royal Air Force, White Waltham, was deeply appreciated.

Members and their guests were received by the President, Dr. H. Roxbee Cox and Mrs. Roxbee Cox from 2.30 - 3 p.m. and the following flying programme began at 3 p.m.:

Aircraft	*Owner*	*Pilot*
Avro Avian	H. M. Woodhams	E. J. Morton
Olympia Eon Sailplane	Surrey Gliding Club	L. Welch
Weihe Sailplane	P. A. Wills	P. A. Wills
(The gliders were towed by an Auster Autocrat owned by British Air Transport Ltd. and flown by Mrs. Ann C. Douglas)		
Cierva Skeeter	Cierva Autogiro Co. Ltd.	H. A. Marsh
Sikorsky Hoverfly II	Ministry of Supply (Lent by Airborne Forces Experimental Establishment)	Flt. Lt. G. Meyrick
Hawker Hart	Hawker Aircraft Ltd.	T. S. Wade
Sopwith Pup	Warden Aviation Company (Shuttleworth Collection)	Group Capt. A. H. Wheeler
D.H. Tiger Moth	Major T. W. Willans and E. S. Morrell	Parachute jump by Major Willans piloted by E. S. Morrell
Miles Messenger	W. S. Shackleton	Miss R. M. Sharpe
Miles Nighthawk	R. Crewdson	R. Crewdson
Miles Sparrowhawk	C. G. Alington	C. G. Alington
Miles Speed VI G	R. R. Paine	R. R. Paine
D.H. Tiger Moth	The London Aeroplane Club	Wing Commander V. R. Moon. (Crazy flying)
Cierva C. 30 Autogiro	B. Arkell	H. A. Marsh
Zaunkoenig	Ultra Light Aircraft Association	Group Capt. E. L. Mole
Aeronca Jap	Lt. Cdr. J. S. Sproule	Lt. Cdr. J. S. Sproule
Chilton Monoplane	Denham Aero Club	G. S. Galt
Fairey Junior	Fairey Aviation Co. Ltd.	J. O. Mathews
Blackburn Bluebird	Blackburn and General Aircraft Ltd.	P. G. Lawrence
Cygnet	Sir Mark Norman, Bt.	Sir Mark Norman, Bt.
Comper Swift	A. L. Cole	A. L. Cole
Percival Gull VI	Percival Aircraft Ltd.	K. S. Arnold
Bleriot Monoplane	Warden Aviation Company (Shuttleworth Collection)	Jeffrey Quill
Deperdussin	Warden Aviation Company (Shuttleworth Collection)	Wing Commander J. A. Kent
Hawker Tomtit	N. F. Duke	N. F. Duke
Avro Tutor 621	Doncaster Ultra Light Aircraft Group	D. Dray
The Balloon	Charles Dollfus	Charles Dollfus

In addition to the many visiting aircraft the following aircraft were on exhibit:—

Type	*Owner*
Sikorsky S. 51	British European Airways
Hawker Cygnet	Hawker Aircraft Ltd. (in hangar)
Supermarine S 6B	Vickers-Armstrongs (Supermarine) Ltd.
Auster Autocrat	Auster Aircraft Ltd. (Goodyear cross-wind landing gear)
D.H. 80A Puss Moth	Airways Aero Club
Chrislea Super Ace	Chrislea Aircraft Co. Ltd.
D.H. Leopard Moth	de Havilland Aircraft Co. Ltd.
D.H. Moth 60G	Maldon C. Harley
Miles Messenger	T. Shipside Ltd.
Percival Q.6	Skyways Ltd.
Miles Magister	R. H. Young
Miles Gemini	Goodyear Tyre and Rubber Co. Ltd.
Supermarine Spitfire	Group Capt. A. H. Wheeler
Aeronca 100	Airways Aero Club

GRAND AEROSTATIC FETE
AT
MAIDENHEAD.

Balloon Ascent,

Under the patronage of the Worshipful the Mayor, and the leading Gentry of Maidenhead and its Vicinity.

Mr. C. GREEN
Aëronaut to the
ROYAL GARDENS, VAUXHALL,
And Proprietor of
GREAT NASSAU BALLOON
With which he performed the memorable Continental Trip
FROM LONDON TO NASSAU IN GERMANY,
A Distance of
580 MILES in 18 HOURS.

Respectfully announces to the Inhabitants and Visitors of Maidenhead and its vicinity, that he purposes making his 402nd, Ascent

On TUESDAY, AUGUST 1st, 1848,
WITH HIS ROYAL
Victoria Balloon

With which he had the honour to ascend from Cambridge, in the presence of her Majesty his Royal Highness Prince Albert, the Duke of Wellington, Sir Robert Peel, and other distinguished Persons, at His Royal Highness's Installation in July last.

This stupendous Aërostatic Machine is formed with 1,200 yard of Silk, manufactured for the express purpose, in alternate gores of Crimson and Gold, with a Zone or Belt, on which is inscribed "ROYAL VICTORIA," in Gold Letters 3 feet high, with Crowns and other National Emblems. It measures 120 feet in circumference, contains 200,000 gallons of Gas, and with the Car attached is

66 FEET HIGH.

The Ascent will take place from a spacious Meadow belonging to Mr. SPRATLY, Builder,
OPPOSITE MAIDENHEAD MOOR.

Programme

To afford the Company an opportunity of inspecting the Balloon, its splendid Car and appendages, the Doors will be opened at 2 o'clock, at 3 o'clock a Balloon formed of Gold-Beaters Skin, resembling a MONSTROUS CLOWN'S HEAD, will be sent up and liberated; At ½ past 3, Mr. Green's PEGASUS after taking a meal of Gas will be allowed to rise to a given height and remain in sight of the Company, this costly figure is formed entirely of Gold-Beaters Skin and is a model of Mr. Green's celebrated **PONY** on which he made several Equestrian Ascents attached to the Balloon without a Car; At ¼ past 4 o'clock

IL SIGNOR PUNCHINELLO

Will make his appearance and ascend without a Balloon to a considerable height where he will promenade and circulate for some time above the Spectators, this Costly and Grotesque Figure is likewise formed of Gold-Beaters Skin; at 5 o'clock the Grand Ascent of Mr. Green & Companions will leave the Earth with the ROYAL VICTORIA and at a considerable elevation

A Parachute containing a Living Animal

Will be launched from the Car which will descend in safety within the Paddock.

During the Inflation of the Balloon
THE SPLENDID BAND
Belonging to the Earl of Orkney's Yeomanry Troops, will play several favourite Airs & Overtures.

TICKETS OF ADMISSION, to witness the Inflation, attaching the Car, & the immediate Ascent from the Earth, ONE SHILLING EACH, to be had at

Higgs and Walker's, Post Office, Maidenhead.

For the accommodation of SELECT VISITORS, more particularly Ladies, a space will be fenced off, commanding the most eligible view of the Inflation and Ascent: admission One Shilling extra each Person.—Children, Half Price.

The Balloon partially inflated with Gas, together with the Car and its Appendages, will be exhibited in the Meadow on Monday the day prior to the Ascent,—Admission, Sixpence each.

Higgs and Walker, Printers, Post Office, Maidenhead.

GRAND AEROSTATIC FETE
AT
MAIDENHEAD.

WHITE WALTHAM AERODROME
MAY
8th
1949

GARDEN PARTY

Under the Patronage of the President of the Royal Aeronautical Society, Dr. H. Roxbee Cox and the Gentlemen of the Council.

Reception
(at the Flag Post)
by the PRESIDENT Dr. H. Roxbee Cox and Mrs. Roxbee Cox
2.30 - 3.0 p.m.

FLYING PROGRAMME
Subject to Alteration — Listen to the Loud Speakers.

Time	Aircraft	Pilot
3.0 - 3.05	Avro Avian	E. J. Morton
3.07 - 3.15	Olympia Eon	L. Welch
	Slingsby T. 21 (if available)	Mrs. A. Douglas
3.17 - 3.25	Westbe	P. A. Wills
3.27 - 3.35	Cierva Skeeter	H. A. Marsh
	Skoraky Hoverfly	Flt. Lt. G. Meyrick
3.37 - 3.45	Hawker Hart	T. S. Wade
3.47 - 3.52	Sopwith Pup	G/Capt. A. H. Wheeler
3.54 - 4.04	Parachute Jump	Major T. W. Williams from D. H. Moth Piloted by E. S. Morrell
	Tea Interval from 4.04 to 4.30 p.m. during which the following will fly in Circus	
4.07 - 4.25	Miles Messenger	Miss R. M. Sharpe
	Miles Nighthawk	R. Crewdson
	Miles Sparrowhawk	C. G. Alington
	Miles Speed VI G	R. R. Paine
4.30 - 4.38	D. H. Tiger Moth	W/Cdr. V. R. Moon
4.40 - 4.48	Cierva C. 30 Autogiro	H. A. Marsh
4.50 - 4.58	Zaunkoenig	G/Capt. E. L. Mole
	Tea Interval from 5.0 to 5.28 p.m. during which the following will fly in Circus	
5.05 - 5.23	Aeronca	Lt/Cdr. J. S. Sproule
	Chilton Monoplane	Commander J. P. Gunner
	Fairey Junior	J. O. Mathews
	Blackburn Bluebird	P. G. Lawrence
	Cygnet	Sir Mark Norman Bt.
	Comper Swift	A. L. Cole
	Percival Gull VI	K. S. Arnold
5.28 - 5.33	Bleriot Monoplane	Jeffrey Quill
5.35 - 5.40	Deperdussin	W/Cdr. J. A. Kent
5.42 - 5.48	Hawker Tomtit	N. F. Duke
5.50 - 5.55	Avro Tutor	John Wroe

The Balloon will go up — with the President — weather permitting — at approximately 6 p.m. Pilot, Charles Dollfus

PARACDUCE DROP by MAJOR C. W. WILLARS
CRAZY FLYING by W/Cdr. V. R. MOON
SEE THE
STUPENDOUS BALLOON!!!
HEAR THE
LUNARDI AIR MARCH
PLAYED BY THE
FAIREY AVIATION BAND
WHICH WILL PLAY FAVOURITE AIRS THROUGHOUT THE AFTERNOON

The President and the Gentlemen of the Council of the Royal Aeronautical Society take this opportunity of thanking all those members and their guests who have joined them on this historic occasion, the Charter Garden Party.
They also wish particularly to thank all those pilots and owners who have so generously helped in the Flying Programme.
Members and their friends are asked specially to read page 53 of the Programme where it has been possible to pay a fuller tribute to all those who have helped; pages 51 & 52 where particulars of the aircraft are given, and page 50 for the full music programme.

The Lewes Press (Wightman & Co. Ltd.) Printers, Lewes

The Flying programme from the 1949 Garden Party Programme. The full Programme was illustrated with a number of reproductions from the Hodgson-Cuthbert collection. On the left of the flying programme is reproduced one of the old Balloon posters from the collection advertising an ascent from Maidenhead in 1848 by Mr. Charles Green in his Nassau Balloon.

The Council wish to thank sincerely all those pilots, private owners, aircraft firms, flying clubs and others who so willingly helped with the display of all aircraft both in the air and on the ground.

The Council also wish to record their thanks to Major Oliver Stewart, M.C. who gave a broadcast description of the events during the afternoon.

Dr. A. Buchanan Barbour, Chief Medical Officer, British European Airways Corporation, was in attendance as the Honorary Medical Officer on the aerodrome.

The Council wish to acknowledge their appreciation of the "Queen Mary" which was kindly provided by Hawker Aircraft Ltd. for the transport of some of the aircraft of the Shuttleworth Collection.

The work of the Royal Air Force Balloon Unit, Cardington, in connection with the Balloon was greatly appreciated.

In addition the Council wish to thank the Berkshire Air Training Corps Squadrons, The Automobile Association, the Royal Automobile Club, the St. John Ambulance Brigade (Berkshire Branch), the Berkshire Constabulary, Pyrene Fire Appliances Ltd. and all those who so readily contributed to making the Charter Garden Party a success.

REVIEWS

FUELS AND LUBRICATING OILS. B. Pugh and J. M. A. Court. Sir Isaac Pitman and Son Ltd., 1949. 169 pp. 51 illustrations. 15s. net.

If ever a book needed writing, this is the one; and if ever a book needed rewriting, this is again the one.

One would have thought that the authors of a short book on fuels and lubricating oils would have desired to keep out of the book as much information as was readily available in the vast literature on these subjects, while at the same time retaining only the basic facts to make the story complete. It is with some surprise, therefore, that one finds on reading this book that whole chapters are written which contain no reference to any source of information either on hydrocarbon chemistry, petroleum processing or the utilisation of fuels and lubricating oils. There is no bibliography.

The introduction of a great deal of elementary hydrocarbon chemistry and openwork formulæ in Chapters I and II, which account for one-third of the text, seriously disturbs the balance of the book, particularly at the expense of the chapters on lubricating oils. In any event, no survey of methods of manufacturing aviation fuels is complete without a reference to superfractionation.

The chapter on combustion is well written, but the chapter on the anti-knock rating of fuels suffers from the fact that the section relating performance numbers to octane numbers is skimped and ignores entirely fuels of weak mixture performance better than 100 octane fuel.

Several re-readings of Chapters VI and VII, which deal with lubricating oils, have completely failed to make the reviewer understand at what precisely the authors are aiming. It is unfortunate that the subject matter of Chapter VII is not related to the title of the chapter "Meaning and Significance of Lubricating Oil Tests."—K.E.W.R.

PERCHANCE. A SHORT HISTORY OF BRITISH NAVAL AVIATION. B. J. Hurren. Ivor Nicholson and Watson Ltd., London 1949. 197 pp. Illustrated and with Index. 10s. 6d.

The title of this book is the motto of the "Perch Club," whose members are a select number of Fleet Air Arm pilots who achieved 100 deck landings before the days of arrester wires. But the title rather belies the subject matter of the book, which is not written in the author's usual lively and humorous style, but is a serious and factual history of the rise of Naval Aviation from the early days of the R.N.A.S., through the "dual control" of the Fleet Air Arm up to the present efficient and up-to-date Aviation Branch of the Royal Navy.

Mr. Hurren must have gone to considerable trouble to gather the details and dates which are incorporated in this instructive book, which should find a place in every reference library. It should be of great interest not only to the Services and those at present engaged in Naval Aviation matters, but also of nostalgic interest to a wide number of people in the Aircraft Industry who have been engaged in the design and production of naval aircraft since the earliest days.—J.H.B.

CORRESPONDENCE

ESTIMATING CRUISING AIR SPEEDS

Mr. Stratford's paper "Estimation of Cruising Air Speeds for Economic Analysis" (February 1949 JOURNAL) is an over-elaborate solution of the level speed equation.

The introduction of the speed for minimum drag and the power required at the minimum drag speed is unnecessary to the solution of the equation and may be misleading to readers who are not familiar with the subject.

The simplest solution of the level speed equation is by means of a chart similar to that given by Barth in Luftwissen, Bd 5 (1938), Nr. 3, and is as follows.

The equation for level speed is

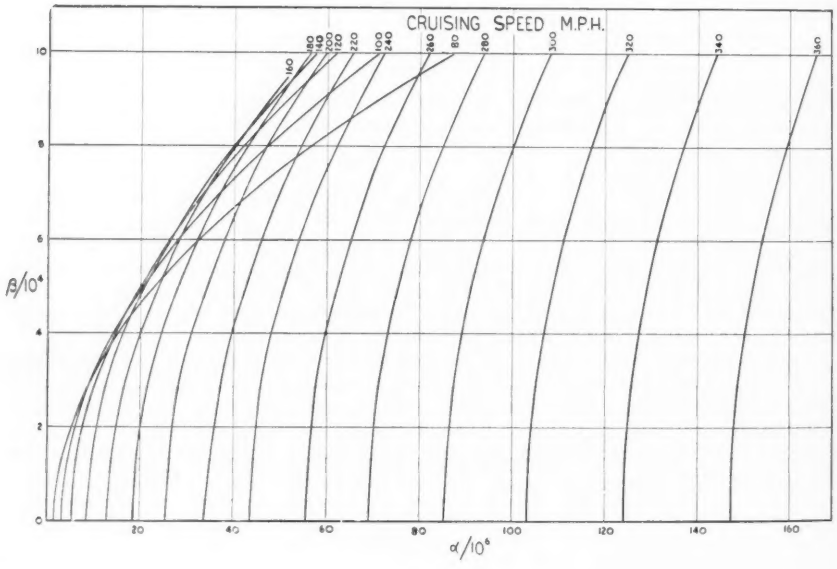
$$550\eta P=\frac{1}{2}C_{D_o}\rho SV^3+\frac{2W^2}{\pi\rho SA_eV} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P is the b.h.p supplied to the propellers, V the level speed in ft./sec., and the other symbols have their usual meaning. This is of the form

$$V^4-\alpha V+\beta^2=0 \, . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where

$$\left.\begin{aligned}\alpha&=\frac{550\eta P}{\frac{1}{2}C_{D_o}\rho S}=\frac{0.4625\times10^6\eta P}{C_{D_o}\sigma S}\\ \beta&=\sqrt{\frac{2W^2}{\frac{1}{2}\pi\rho^2S^2A_eC_{D_o}}}=\frac{0.04744\times10^4W}{\sigma S\sqrt{(A_eC_{D_o})}}\end{aligned}\right\}\ \text{with } \rho_o=0.00237835 \text{ slugs/ft.}^3 \quad . \quad (3)$$



To determine the cruising speed, α and β are calculated for the given conditions and the speed in m.p.h. is read directly from the chart, which can be drawn to any scale to give the desired degree of accuracy.

The method is particularly amenable to changes in the parameters, as can be seen from the form of α and β. If η or P is changed the abscissa α can be scaled up accordingly and the new cruising speed read from the chart; or if W is changed, β is scaled up. For a change of height, both abscissa and ordinate are scaled in the ratio of the values of σ.

The application of the chart to Mr. Stratford's two examples is as follows:—

(*i*) Calculation of true cruising speed for design study.

Data: W, S, C_{D_0}, A_e, P, η and σ.

(*a*) Calculate $\alpha/10^6$ and $\beta/10^4$ from (3)

(*b*) Read cruising speed from chart.

(*ii*) Calculation of corrected true cruising speed after alteration of operational parameters.

Data:

Initial W_1, S_1, P_1, η_1, σ_1, V_1, C_{D_0} and A_e

Final W_2, S_2, P_2, η_2, σ_2

assuming C_{D_0} and A_e are constant, find the final value of V, *i.e.* V_2.

$\alpha/10^6$ and $\beta/10^4$ will have been calculated already in the determination of V_1.

(*a*) Multiply $\alpha_1/10^6$ by $\dfrac{\eta_2}{\eta_1} \times \dfrac{P_2}{P_1} \times \dfrac{\sigma_1}{\sigma_2}$

and $\beta_1/10^4$ by $\dfrac{W_2}{W_1} \times \dfrac{\sigma_1}{\sigma_2}$.

(*b*) Read off V_2 from the chart.

E. C. Pike, *Associate Fellow.*

MR. STRATFORD'S REPLY

The reference by Miss Pike to the solution of the level speed equation by the graphical method of Barth is of general interest since this is clearly a direct and simple approach. Nevertheless, it omits certain steps which, in practice, are of value in the study of many problems in operational performance analysis and transport economics. I can hardly claim the space to cover all the types of problem encountered, but the following notes may indicate some aspects of the subject.

u, the speed for minimum drag is a valuable parameter and occurs in most solutions of the problem. Miss Pike has suggested that the use of u may be misleading but in fact, in the alternative method she presents, it is also calculated in the form $\beta = u^2$. In Fig. 1 of my paper a graphical solution for u is offered which is convenient and has an applicability to other performance problems.

Since some emphasis has been given to the calculation of n and p, the speed and power ratios, perhaps some further explanation is justified since this was cursorily treated in my published note.

In the operational and economic analysis of transport aircraft performance, the value of the speed ratio n is of prime importance in indicating the position of the operating point in the cruising domain and for showing what margin—if any—exists above the minimum comfortable cruising threshold.

This factor is made the more important by the high altitudes of operation of the new generation of post-war transport aircraft with high wing loadings and high

efficiency flaps and by the rapid fall off in output of the gas turbine with increasing altitude. In the engine "cut" cases, for example, after *en route* failure, a loss of altitude may be necessary if the engine cruising limitations are not to be exceeded, and under such changed conditions the position of the new operating point in the cruising domain is most rapidly apparent by a correction on the "$n-p$" chart, as previously described, and an inspection of the new value of n. A similar problem arises in "half power off" flight for best endurance—a condition which may well provide a key to turbine fuel reserve difficulties.

As a further application it may be of interest to note that for certain values of n (or C_L) we should expect changes in the C_{D_0} of a laminar flow wing.

The principal value of the power ratio p, like the parameter α in Barth's method, is that it provides an immediate indication of the effect of power changes on speed. However, when n only is needed the calculation of α may be obviated by means of the power ratio, and where V also is required there is little to choose between the two methods.

One joint application of the speed and power ratios is in the relation, air miles per gallon $=$ const. $\frac{n}{p} \times \frac{1}{w}$ for a given propeller efficiency and specific consumption. This is of use in the economic assessment and comparison of payload and range. Some of these problems in analysis require more than the solution of the level speed equation and it has been found that non-dimensional methods are practical and rapid.

Alan H. Stratford, *Associate Fellow.*

AIRLINE ENGINEERING SERVICE EXPERIENCE

In the paper "An Airline's Engineering Service Experience and its Use in the Design of Transport Aircraft" by H. S. Crabtree (February 1949 JOURNAL) the author points out the value, to the aeroplane designer, of the operator's statistical records. It cannot be gainsaid that the utilisation of such records should enable the designer to improve the servicing and maintenance features of his new creations, and the following comments should not be construed as minimising in any manner the importance, to the designer, of operating statistics.

In emphasising the effects of servicing requirements upon aircraft utilisation, the author presents some interesting data on utilisation, working life, and vehicle cost for transport aircraft, motor bus and ocean liner. Using the maximum figure of the range in each instance, it is evident that, on a per pound weight empty basis, the transport aeroplane is 109 times as costly as the ocean liner; and has 0.4 the utilisation rate and one-fifth the working life thereof. Comparing the transport aeroplane with the bus (double-decker), it is about 17 times as costly, has one-half the utilisation rate, and about one-half the working life.

These are striking comparisons which might, without further consideration, lead one to conclude that the transport aeroplane is irremediably burdened with characteristics which render it incapable of competing financially with other transport vehicles. It may be of interest, therefore, to examine these characteristics further, in the light of certain related factors.

Costs are given in the paper on a per pound weight empty basis. Since the transport of passengers is the primary function of the transport aeroplane, the bus, and the ocean liner, a more significant index of initial cost is the cost of the vehicle per passenger carried. While there is an appreciable variation in passenger capacity for a given weight of any particular type of vehicle, depending upon the space allotted to passenger amenities, provisions for carrying cargo, and other factors, the following figures are believed to be reasonably representative:

Vehicle	*Cost per pound weight empty	Weight empty lb. per passenger	Cost per passenger
Transport aircraft	£5	1,000	£5,000
Bus	6s.	†400	£120
Ocean liner	11d.	55,000	£2,500

TABLE I

* The maximum of the range given in the author's paper is shown in each case.
† Single deck (U.S.).

It now appears that the aeroplane is twice as costly as the steamship, on a per passenger capacity basis, as compared with 109 times on a basis of per pound cost. On the other hand, the aeroplane is 42 times as costly as the bus, on a per passenger capacity basis, as compared with 17 time on a basis of per pound cost.

A more revealing comparison is furnished on a basis of total mileage per vehicle throughout its working life. Again using the maximum figures for the ranges in each instance, as given in the paper, and assuming the average speeds shown, the following comparison results:—

Vehicle	Utilisation Hours per year	Working life Years	Speed m.p.h.	Total miles working life
Transport aircraft	2,920	7	300	6,132,000
Bus	5,840	12	40	2,803,000
Ocean liner	7,300	35	20	5,110,000

TABLE II

Thus, on a "working life miles" basis the aeroplane shows a superiority of about 20 per cent. over the ocean liner, and more than twice that of the bus.

From these two comparisons, a third is immediately suggested—Cost of vehicle per passenger-mile capacity over its working life. This comparison is shown below.

Vehicle	Cost per passenger (Ref.: Table I)	Total miles working life (Ref.: Table II)	Vehicle cost per 1,000 passenger-miles
Transport aircraft	£5,000	6,132,000	16s. 4d.
Bus	£120	2,803,000	10d.
Ocean liner	£2,500	5,110,000	9s. 10d.

TABLE III

On this basis the initial cost of the aeroplane is shown to be about 67 per cent. greater than that of the ocean liner, and about 20 times greater than that of the bus.

It is thus seen that the initial cost of the transport aeroplane is more truly somewhat less than twice that of the ocean liner, rather than more than 100 times. Increases in both utilisation and working life, beyond those given in the paper, appear to be attainable by improved design, which should bring the initial cost of the aeroplane very close to that of the liner, on a passenger-mile capacity basis.

It should be observed, however, that the passenger load factor realised in actual operation, which is influenced by many factors such as government regulations, schedules, traffic available, weather, and so on, will be less favourable for the aeroplane than for the steamship.

The cost of the transport aeroplane still compares quite unfavourably with that of the bus, on any basis, but since the bus is essentially a short-haul vehicle, the comparison is not particularly valid.

Walter R. Jones, *Associate Fellow,*
Lockheed Aircraft Corporation.

MR. CRABTREE'S REPLY

Mr. Jones' contribution is extremely valuable as it endorses again, and this time from the aircraft manufacturer's viewpoint, the necessity of the aircraft operator concentrating upon obtaining high utilisation rates of work with his aircraft, if he is to make his operations self-sufficient and independent of subsidies.

In Mr. Jones' Table III, he shows the cost of a modern aircraft as 16s. 4d. per thousand passenger-miles, or about one-fifth of a penny per passenger-mile. This figure he obtained by taking my upper figure of 2,920 hours for aircraft utilisation.

If we evaluate this cost of vehicle per thousand passenger-miles for varying utilisation rates, using the same figures for cruising speed, aircraft life, and so on, the effect of increasing utilisation is shown even more clearly:—

Utilisation rates (Hours per annum)	Vehicle cost per 1,000 passenger-miles (in shillings and pence)	Cost per passenger-mile (in pence)
500	95s. 2d.	1.14
1,000	47s. 7d.	0.57
1,500	31s. 9d.	0.38
2,920	16s. 4d.	0.19
4,000	11s. 10d.	0.14
6,500	7s. 3d.	0.087

In other words the aeroplane cost (spread over potential passenger-miles) becomes cheaper than the ocean-going ship costs, when the aeroplane is operated consistently for more than four thousand hours each year. This is quite apart from other overhead charges which the airline has to spread over its aircraft hours of operation each year. All experienced airline engineers will confirm that to obtain consistently utilisation rates year in and year out of over three thousand hours with existing civil aircraft is virtually impossible.

Yet the attainment of these high rates of utilisation appears to be the only way air transport will be freed from the necessity of subsidies and reach the position where it can honestly lower its passenger and freight rates, and so offer mass travel and competitive cargo rates, both of which will be capable of earning a profit.

Aircraft capable of being operated to these rates of utilisation will not be built by wishful thinking, nor by theoretical dreams of a manufacturer's design office, or of an operator's isolated development department. They will only be built when all the details of maintenance and overhaul work on existing aircraft are thoroughly and conscientiously studied by an aircraft manufacturer's design team and the whole complex planning for efficient maintenance is considered jointly, by both the manufacturer and the operator during the design stage of the new aircraft.

In my paper I endeavoured to sketch in the bare outlines of the method by which this work could be undertaken.

H. S. Crabtree, *Associate Fellow.*

an appreciation

THE COUNCIL OF THE ROYAL AERONAUTICAL SOCIETY WISH TO THANK THOSE COMPANIES WHO, BY THEIR GENEROUS CO-OPERATION, HAVE DONE SO MUCH TO HELP IN THE PRODUCTION OF THE JOURNAL

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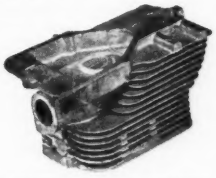

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The Journal is published monthly at the Offices of the Society, 4 Hamilton Place, Piccadilly, London, W1. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. Subscriptions per annum, £4 13 0 including postage; Single Numbers 7/6 or 7/9 post free. All communications for publication or Advertisements in the Journal, or on general matters affecting the Society should be addressed to—The Secretary, J. Laurence Pritchard, 4 Hamilton Place, W1. The Society's Bankers are Messrs. Coutts & Co.

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THE ROYAL AERONAUTICAL SOCIETY

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NOTICES AUGUST 1949

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Fatigue of Aircraft Structures, by P. B. Walker, M.A., Ph.D., F.R.Ae.S.

Industrial Wind Tunnels, by D. L. Ellis, B.Sc., A.R.T.C., F.R.Ae.S.

The 1949 Garden Party.

Reviews.

Correspondence.

The Council have set aside an annual sum of £250 *for the award of premiums for papers published in the Journal and hope that members (or non-members) will contribute papers on their own special subjects.*

THE AERONAUTICAL QUARTERLY

The second number of "The Aeronautical Quarterly" will be published in August. Copies will be obtainable from the offices of the Society, 4 Hamilton Place, W.1, about the middle of August, at 7s. 9d. each to members of the Society, post paid, or 10s. 3d. each to non-members. The contents of the second number are:—

Displacements of a Linear Elastic System under a Given Transient Load	D. Williams
Skin Friction in the Laminar Boundary Layer in Compressible Flow	A. D. Young
A Simplified Theory of "Simple Waves"	A. Ghaffari
The Measurement of Gas Turbine Combustion Efficiency by Gas Analysis	L. J. Richards and J. C. Street

The first number, of which copies are still available, contains the following papers:—

Control Reversal Effects on Swept-back Wings	H. Templeton
Calculation of Downwash Behind a Supersonic Wing ..	G. N. Ward
Estimation of the Effects of a Parameter Change on the Roots of Stability Equations	K. Mitchell
Flutter of Systems with Many Freedoms	W. J. Duncan
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Determination of the Drag of Jet-Propelled Aircraft in Flight	G. W. Trevelyan and D. R. Blundell
Notes on the Linear Theory of Incompressible Flow Round Symmetrical Swept-back Wings at Zero Lift	F. Ursell

BIRTHDAY HONOURS

The President and Council congratulate the following members whose names were included in the Birthday Honours List:—

K.B.E.—Air Chief Marshal Sir James Robb, K.B.E., C.B., D.S.O., D.F.C., A.F.C., Associate Fellow.

C.B.—Mr. W. G. A. Perring, Fellow.

O.B.E. (Civil Division)—Mr. J. S. Clarke, Ph.D., D.Sc., Associate Fellow.
O.B.E. (Military Division)—Group Captain G. Silyn-Roberts, A.F.C., M.Sc., Fellow.
King's Commendation for Valuable Service in the Air—Engineer 1A G. N. T. Hemmings, Student.

AERONAUTICAL STUDIES IN THE UNIVERSITY OF LONDON

The Secretary has received a letter from the Academic Registrar of the University of London which states *inter alia*:—

"As you are aware, the question of aeronautical studies in the University of London has been exhaustively explored recently by the Faculty of Engineering in the University, and representatives of your Society have very kindly given to the Faculty the benefit of their advice and guidance in this matter. I am therefore writing to inform you that the University Senate at their recent meeting resolved (*a*) that a Board of Studies in Aeronautical Engineering be established within the Faculty of Engineering and (*b*) that the personnel of the Board for the remainder of the year be as follows:—

Appointed Teachers of the University: Professor A. A. Hall, Dr. N. A. V. Piercy, Professor S. J. Davies, Professor O. A. Saunders, Professor G. Temple.
Recognised Teachers of the University: Mr. W. E. Dumbrill, Mr. F. T. Hill."

PROCEEDINGS OF SECOND AERONAUTICAL CONFERENCE

The Proceedings of the Second Anglo-American Aeronautical Conference, containing the 23 papers read by British and American Lecturers at the Technical Sessions in New York from 24th-26th May 1949, are to be published in one Volume by the Institute of the Aeronautical Sciences. It is hoped that the Proceedings will be ready about January 1950. The price has been fixed by the Institute at 15 dollars (£3 15s. 0d. at the present exchange rate of 4 dollars to the pound).

Copies may be ordered through the Society and it will greatly help both the Society and the Institute if members will place their orders for the Proceedings as quickly as possible.

MEMBERS NEW APPOINTMENTS

Mr. A. A. Bage, Fellow, to be Assistant Chief Designer, A. V. Roe & Co. Ltd.

BRITISH COMMONWEALTH AND EMPIRE LECTURE

The Fifth British Commonwealth and Empire Lecture will be given by Mr. E. H. Atkin, F.R.Ae.S., Chief Designer, Airframe Division, A. V. Roe Canada Ltd., on Thursday, 15th September 1949 at 6 p.m. at the Institution of Civil Engineers, Great George Street, London, S.W.1. Tea will be served at 5.30 p.m.

The title of the Lecture will be: "Inter-City Transport Development on the Commonwealth Routes."

LECTURE PROGRAMME—AUTUMN SESSION 1949

The first two lectures of the Autumn Session, which will be held at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, London, S.W.1 (tea at 5.30 p.m.), will be—

Thursday 15th September 1949—Fifth British Commonwealth and Empire Lecture—Inter-City Transport Development on the Commonwealth Routes, by E. H. Atkin, F.R.Ae.S.

Thursday, 6th October 1949—Aircraft Design Analysis Methods as Employed by the Research Division of the Bureau of Aeronautics, U.S. Navy Department, by Ivan H. Driggs, A.E., F.R.Ae.S., F.I.Ae.S.

Visitors are welcome to attend the Lectures, but must have tickets, which are obtainable through members of the Society.

GRADUATES' AND STUDENTS' SECTION

Saturday 10th September 1949—Visit to London Airport, Heath Row, at 2.45 p.m. Members wishing to take part in this visit should inform the Assistant Hon. Secretary, D. A. Thurgood, Sunnyside Bungalow, Portsmouth Road, Ripley, Surrey, not later than 1st September 1949.

BRANCH LECTURES—AUTUMN SESSION 1949

COVENTRY BRANCH

Wednesday 21st September 1949—Rocket Propulsion, by Air Commodore Dann.

Wednesday 19th October 1949—The London Sydney Air Route, by C. H. Jackson.

Wednesday 16th November 1949—Aircraft Structures, by Dr. P. B. Walker, F.R.Ae.S.

Wednesday 14th December 1949—Film Evening on Aircraft Materials.

Meetings are held in the Trinity Hall (near Pool Meadow) Coventry at 7.30 p.m.

LUTON BRANCH

Wednesday, 7th September 1949—Air Liner Operation, by a Senior Pilot and Ground Control Officer of British European Airways.

Wednesday 5th October 1949—Film Show.

Wednesday, 2nd November 1949—Gas Turbine Development, by a member of the National Gas Turbine Establishment.

Wednesday 23rd November 1949—Aeronautical Brains Trust.

Wednesday, 7th December 1949—Role of Aircraft in Future Warfare, by Air Marshal Sir Robert Saundby, K.B.E., C.B., M.C., D.F.C., A.F.C.

Wednesday 14th December 1949—Annual General Meeting and Presidential Address.

Meetings are usually held at the George Hotel, Luton, at 7.30 p.m.

ASSOCIATE FELLOWSHIP EXAMINATION DECEMBER 1949

Candidates are reminded that the December examination will be the last date on which papers will be set in the old syllabus. Papers are still available for the past four years at 2/2 per set (including postage). Entry forms, with fees, must be received by 30th September 1949, but it would help the organisation of the examinations if candidates would inform the Secretary as soon as possible of their intention of taking the examination. Entries for the new Syllabus must be received by 31st August 1949.

RESULTS OF ASSOCIATE FELLOWSHIP EXAMINATIONS, MAY 1949

HOME

The following were successful in the Associate Fellowship Examinations held in May 1949:—

M. Ali, Theory of Machines; N. W. Barford, Aerodynamics; C. R. P. Barlow, Theory of Machines, Pure Mathematics; N. A. H. Barraud, Strength of Aeronautical Materials and Structures; N. W. M. Beatts, Strength of Aeronautical Materials and Structures, Pure Mathematics; G. T. Biermann, Design (Aircraft); R. A. Blythe, Pure Mathematics; E. L. Bond, Strength of Aeronautical Materials and Structures; H. C. Bowell, Theory of Internal Combustion Engines; C. R. Broughton, Design (Aircraft), Theory of Machines; W. Burley, Air Transport, Pure Mathematics; R. S. Capewell, Theory of Internal Combustion Engines; J. B. P. Causley, Design (Aircraft), Pure Mathematics; H. K. Cartwright, Theory of Internal Combustion Engines; W. P. Carrivick, Pure Mathematics; A. D. Chapman, Design (Aircraft), Applied Mathematics; W. E. Coe, Pure Mathematics; A. L. Cole, Theory of Internal

Combustion Engines; P. H. Cook, Pure Mathematics; E. N. Crabbe, Design (Aircraft); G. St. Q. Crocket, Aerodynamics, Pure Mathematics; J. S. Dean, Aerodynamics; G. P. Dollimore, Strength of Aeronautical Materials and Structures; P. C. Donovan, Theory of Machines, Pure Mathematics; P. J. Farmer, Pure Mathematics; J. C. Geering, Strength of Aeronautical Materials and Structures, Aerodynamics; N. Ghose, Theory of Machines (1st place), Theory of Internal Combustion Engines; F. S. Glew, Strength of Aeronautical Materials and Structures; C. A. Glew, Theory of Machines, Theory of Internal Combustion Engines; T. W. Godden, Air Transport (1st place); J. H. Gordon, Applied Mathematics; W. E. Hagan, Applied Mathematics; J. W. Haggas, Strength of Aeronautical Materials and Structures, Pure Mathematics, Applied Mathematics; T. M. Hainsselin, Strength of Aeronautical Materials and Structures; L. G. Hall, Pure Mathematics; J. D. Hallett, Strength of Aeronautical Materials and Structures, Pure Mathematics; W. J. Harbottle, Strength of Aeronautical Materials and Structures, Theory of Machines; J. P. Harris (Miss), Aerodynamics; C. J. Hart, Applied Mathematics; P. A. Hilton, Strength of Aeronautical Materials and Structures; J. H. Hurford, Pure Mathematics; R. V. Hurrell, Aircraft Instruments—Theory and Design; F. Jackson, Pure Mathematics; D. K. Kapur, Applied Mathematics; R. N. Kashyap, Aerodynamics; J. N. Kirkby, Strength of Aeronautical Materials and Structures; M. Kishor, Applied Mathematics; A. G. Kurn, Theory of Internal Combustion Engines; G. W. Little, Strength of Aeronautical Materials and Structures; K. J. Mackenzie, Pure Mathematics; J. G. Male, Aerodynamics; H. J. F. Manners, Theory of Machines; J. C. Martin, Strength of Aeronautical Materials and Structures; E. J. Martin, Theory of Internal Combustion Engines; J. Mawer, Pure Mathematics; R. D. W. Miller, Strength of Aeronautical Materials and Structures, Theory of Machines, Aerodynamics; J. O. Montanaro, Theory of Machines, J. L. Mort, Design (Aircraft); A. K. Mubarak, Pure Mathematics; K. K. Mukerjee, Pure Mathematics; D. Nayler, Pure Mathematics (1st place); J. S. Nayler, Strength of Aeronautical Materials and Structures; J. M. Nelmes (Miss), Theory of Machines, Pure Mathematics; N. N. Nicholls, Pure Mathematics; J. C. Pathak, Meteorology and its Application to Aeronautics; J. W. Paulsen, Pure Mathematics; L. R. Pool, Applied Mathematics (1st place); A. T. Pugh, Strength of Aeronautical Materials and Structures; B. E. Rayner, Strength of Aeronautical Materials and Structures, Pure Mathematics; B. Reynolds, Strength of Aeronautical Materials and Structures; W. W. Ringland, Design (Aero Engines), Theory of Internal Combustion Engines, Applied Mathematics; P. T. Ross, Strength of Aeronautical Materials and Structures; H. M. Roy, Pure Mathematics; M. Saeed, Pure Mathematics; D. Shellard, Pure Mathematics; E. Slap, Theory of Machines, Theory of Internal Combustion Engines; A. W. J. Smith, Design (Aero Engines); M. F. Smith, Strength of Aeronautical Materials and Structures, Pure Mathematics; A. E. Southgate, Theory of Internal Combustion Engines, Aerodynamics, Pure Mathematics; J. M. Spong, Applied Mathematics; R. G. Spencer, Design (Aircraft), Theory of Machines, Pure Mathematics; G. C. Sugden, Aerodynamics, Applied Mathematics; J. A. Swingler, Theory of Machines; C. R. Taylor, Pure Mathematics; E. Toner, Applied Mathematics; P. E. Tweed, Strength of Aeronautical Materials and Structures; A. Uydens, Strength of Aeronautical Materials and Structures; H. Vogel, Pure Mathematics; J. G. Wakeford, Design (Aircraft); P. E. Walters, Pure Mathematics; K. W. Watkins, Pure Mathematics; K. R. Warren, Air Transport; J. M. Williams, Strength of Aeronautical Materials and Structures; P. J. Wingham, Theory of Machines, Aerodynamics (1st place), Pure Mathematics; P. A. Woolf, Pure Mathematics; W. B. Wright, Theory of Internal Combustion Engines; J. Wyatt, Applied Mathematics; M. A. Yusef, Strength of Aeronautical Materials and Structures.

NEW SYLLABUS ENTRIES

B. R. A. Burns, Pure Mathematics; Properties of Matter, Heat, Light and Sound; Aerodynamics I; Strength of Aircraft Materials and Theory of Structures I.

B. M. Laven, Pure Mathematics; Aerodynamics I; Strength of Aircraft Materials and Theory of Structures I.

ABROAD

The following were the successful candidates in the Associate Fellowship Examintions held in May 1949 abroad:—

C. G. Andrews (Wellington, New Zealand), Strength of Aeronautical Materials and Structures; W. J. Bouma (Amsterdam, Holland), Air Transport; V. R. Bunyard, (Port Elizabeth, South Africa), Strength of Aeronautical Materials and Structures, Aircraft Materials; J. W. Davison (Auckland, New Zealand), Strength of Aeronautical Materials and Structures, Aircraft Materials; S. Emer (Calgary, Canada, Pure Mathematics; R. S. Gopalachar (Bangalore, India), Strength of Aeronautical Materials and Structures; C. J. Horne (Calgary, Canada), Pure Mathematics, Strength of Aeronautical Materials and Structures; W. G. Johnson (Malaya), Applied Mathematics; S. V. Karandika (Bombay, India), Pure Mathematics, Aerodynamics; N. Krishnappa (Bangalore, India), Strength of Aeronautical Materials and Structures; C. L. Matthews (Calgary, Canada), Pure Mathematics, Strength of Aeronautical Materials and Structures, Aircraft Materials; F. A. A. Palmer (H.M.S. *Falcon*, Malta), Theory of Internal Combustion Engines; H. A. R. Rao (Bangalore, India), Theory of Internal Combustion Engines; M. R. Roper (Wellington, New Zealand), Aircraft Materials (1st place); H. A. Schilling (Calgary, Canada), Pure Mathematics; K. R. Simpson (Calgary, Canada), Aircraft Materials; K. S. Suryanarayanan (Bangalore, India), Strength of Aeronautical Materials and Structures (1st place), Design (Aircraft); L. G. Thomas (Calgary, Canada), Pure Mathematics, Strength of Aeronautical Materials and Structures.

POSTS AT THE ROYAL AIRCRAFT ESTABLISHMENT

UNESTABLISHED POSTS: Applications are invited by the Ministry of Supply for unestablished posts, at the Royal Aircraft Establishment, Farnborough, for work connected with specification of scientific requirements and development of designs for large wind tunnels and other aerodynamic research equipment:—

*C.*473/49*A*—Senior Scientific Officer for work including design of tunnel air circuits, particularly assessment of characteristics of fans and compressors.

*C.*474/49*A*—Senior Scientific Officers and Scientific Officers for work including design of supersonic nozzles and other parts of tunnel air circuits; planning detailed requirements for instrumentation and observation, calibration and operation of plant for experimental work and aircraft development.

Candidates must possess a good honours degree or equivalent in mathematics, physics or engineering. A knowledge of aerodynamics, compressor design or related subjects and experience in above duties would be desirable.

Starting salary assessed on age, qualifications and experience within following ranges, plus F.S.S.U. benefits (applicants for senior grade must be 26 years of age or over).

Senior Scientific Officer	..	£670-£860
Scientific Officer	.. ..	£380-£620

Rates for women somewhat lower.

Write, quoting appropriate number to Technical and Scientific Register (K), York House, Kingsway, London, W.C.2, for application forms which must be returned by 27*th August* 1949.

EXPERIMENTAL OFFICERS: Applications are invited by the Ministry of Supply for posts in the following grades at the Royal Aircraft Establishment, Farnborough, for work connected with the design and development of large wind tunnels and associated aerodynamic research equipment:—

Senior Experimental Officer	..	£705-£895
Experimental Officer	.. ..	£495-£645

Rates for women somewhat lower.

Candidates must possess at least H.S.C. or equivalent with mathematics, physics or engineering as principal subject. Experience in design or use of experimental equipment or scientific instruments is required, with specialised knowledge of one or more of following subjects: Instrumentation and observation apparatus, *e.g.*, wind tunnel balances, manometers, optical devices, printing and recording gear; electronic equipment; control gear for driving motors and air conditioning plant.

Grade and starting pay according to age, qualifications and experience (applicants must normally be 35 years of age or over for senior grade and 28 or over for the other grade); the posts are unestablished.

Write, quoting *C.*475/49*A* to Technical and Scientific Register (K), York House, Kingsway, London, W.C.2, for application forms which must be returned by *3rd September* 1949.

PRINCIPAL SCIENTIFIC OFFICERS: Applications are invited by the Ministry of Supply for the following posts in Principal Scientific Officer grade at the Royal Aircraft Establishment, Farnborough:—

*C.*470/49*A*—Carry out and supervise research into fatigue of aircraft structures. Candidates must have good honours degree in engineering with sound knowledge of aircraft structures, supported by design experience.

*C.*471/49*A*—Take charge of section carrying out research into behaviour of materials and structural elements for use of aircraft designers and to co-ordinate similar work undertaken for the Ministry of Supply by the Aircraft Industry. Candidates must have good honours degree in mathematics, physics or engineering with sound knowledge of structural principles, materials and metallurgy.

*C.*472/49*A*—Carry out and supervise research into fundamental theory of structures, primarily from standpoint of aircraft. Candidates must have good honours degree in mathematics or engineering with experience in work on stress diffusion, shear lag and allied subjects.

Posts are unestablished but carry F.S.S.U. benefits. Candidates must be at least 31 years of age; starting salary within range £910-£1,177 according to age, qualifications and experience (rates for women somewhat lower).

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ELECTIONS

The following is a list of new members and transfers of membership of the Society:

Fellows

Arthur Lorne James (from Associate Fellow), Elizabeth Muriel Gregory MacGill (from Associate Fellow), John Knudsen Northrop.

Associate Fellows

William Liddiard Amer, Kenneth Charles Ball (from Graduate), Howard John Bell-Walker, Cornelis Johannes Marinus Benard, Frederick Thomas Bevan (from Associate), Derek LeRoy Bird (from Graduate), Arnold Amherst Buchanan, William Augustus Cheesewright, Stanley William Chisman (from Graduate), Peter Rowland Crewe, Ivor Macaulay Davidson (from Student), Harold Davies, Herbert David Denchfield (from Student), Eric Downham, Eric John Earnshaw, Albert George Mark Elliott (from Graduate), Roy Fairclough, Lorenzo Pedro Fontana, Howard Stanley Fowler (from Graduate), Kathleen Margaret Fowler, Denys Thomas Glover, Gustaf Gudmundson (from Associate), Ronald Frank Wortley Guest, John Maxwell Hands (from Graduate), John Jack, Vincent Peter Kelly, Derek Joseph Lambert (from Graduate), John Albert Lawford, Herbert John Sherwood Leslie, Marian Josef Kazimierz Lesniak, Kelvin Oliver Lockyear (from Graduate), William James Johnstone Macdonald (from Graduate), John Irwin McKillop, George Maurice Martin Magill (from Graduate), Maurice George Marsh (from Graduate), Rodney Melling (ex-Student), Wilfred Ernest Martin Miller (from Associate), Charles Reginald Milne (from Graduate), Pierre Moraux, Ian Thomas Alexander Murchie (from Graduate), Beryl Catherine Myatt (from Student), Keith Robert Obee (from Graduate), Frank Cyril Petts (from Associate), Lewis Raymond Phillips (from Graduate), Peter Scott Pickles, Robert Hillson Poynton, Eric Francis Price, Joseph McAdam Rainey (from Graduate), Gwendolen Marjorie Roper, Duncan Saunders (from Graduate), Edward Simpson (from Associate), Robert Skinner (from Graduate), Peter Egbert Arthur Stevenson (from Student), Walter Henry Soutar (ex-Student), Leonard Livingstone Summers, Dennis Ian Thompson (ex-Student), Jack Percival Thompson (from Associate), David Herbert Whaley (from Graduate).

Associates

Herbert Denis Burke, Richard Carrall, Percy Edmund Walter Chorley, Wilfred Henry James Dibbens, Jack Drew, Irene Joy Ferguson, Battista Louis Gagliardi (from Companion), Victor Arthur Gittins, Roy Holland, Kenrick Jones, John Alexander Kent, Arthur Nigel Kitching, Fredrick Godson Ling, Harold Luskin, Laurence Malec, Harold Maurice Newton, William Hamilton Oliver, Gartrell Richard Ian Parker, Ernest Lane Pearson, George Raymond Roscoe, Richard Brian Stratton, John Syrad (from Student), Leslie Taylor, Thomas Russell Thomson, Ian Tongue (from Student), John William Thomas Wheeler, Thomas Alfred Yates.

Graduates

Alan Leonard Baker (from Student), Rollin Hamilton Bates (from Student), Connell Frederick Bee (from Student), Raymond Arthur Birch, Fred Bradshaw, Ronald Hugh Campbell, John Frederick Cannell (from Student), Kenneth John Coleman (from Student), Leslie Cedric Collins, James Percival Crossley, John Harold Drake (from Student), David Swales Forsyth, John Alan Fuller, Alan Stanley Gander, Reginald Bertram Glanville-Wood (from Student), Bernard Irvin Grant, Stanley Gray, Donald Griffiths, Kenneth Ronald Guy (from Student), James Charles Hateley, Patrick Alan Hatswell, John Arthur Godfrey Holmes, William Donald Horsfield (from Student), George John Houghton (from Student), Albert Hayden George Jeffery, Rajendra Nath Kashyap, Eric Dorian King (from Student), Ernest Fintan Lawlor (from Student), Leslie Walter Lawrence (from Student), Philip George Lockington (from Student), John McCulloch (ex-Student), Archibald Bathgate McKenzie (from Student), David Albert Needs, James Antony Rowland (from Student), Kenneth Osborn Scott, Ronald George Smith, John Trevor Stamper (from Student), Trevor Edwin Arthur Stevenson (from Student), Peter Latham Sutcliffe (from Student), Robert Lindsay Whiteley (from Student).

Students

San Hla Aung, Aland Leslie Hall, Donald Peter Charles Kemp, Kenneth Cuthbert Kinghorn, Alan Knight, Aubrey Benjamin Knight, William Henry Napthine, Krishnan Aditya Varman Pandalai, Clerwyn David Roberts, Rakhal Das Saha, Richard George Spencer.

Companions

John Scholes Aked, Frank Henry Bellis, C. R. Rajagopal.

ACKNOWLEDGMENTS

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ADDITIONS TO THE LIBRARY

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

A.a.365—Computation Curves for Compressible Fluid Problems. C. L. Danley and F. C. Wood. John Wiley & Sons. 1949.

B.e.49—Stunt Control Line Flying. R. H. Waring. Percival Marshall. 1949.

D.e.42—Economic Consequences of Air Power. J. Carlton Ward. Library of Congress. 1949.

E.b.137—Sources of Engineering Information. B. H. Dalton. University of California Press. 1948.

E.b.138—Fundamentals of Stress Analysis. Volume I. A. Deyarmond and A. Arslan. Aero Publishers, California. 1942.

E.b.139—The Fowler Flap. H. D. Fowler. Wetzel Publishing Co., California. 1948.

E.g.14—Comptes Rendus des Journées de la Grosse Forge. Chambre Syndicale de la Grosse Forge Française. 1948.

EE.f.52—Introduction to the Gas Turbine. D. G. Shepherd. Constable & Co. 1949.

EE.h.45—Jet Propulsion Turbojets. V. C. Finch. National Press. 1948.

EE.h.47—Fundamentals of Gas Turbine Technology. W. R. Thomson. Power Jets Ltd. 1949.

EE.h.48—Gas Turbines for Aircraft. F. W. Godsey and L. A. Young. McGraw Hill Book Co. 1949.

F.b.46—Flight Refuelling. C. H. Latimer Needham. Flight Refuelling Limited. 1949.

G.a.85—Literature Survey on the Low-Temperature Properties of Metals. A. E. White & C. A. Siebert. Edwards, Ann Arbor, Michigan. 1947.

I.c.45—Fluid Dynamics. V. L. Streeter. McGraw Hill Book Co. 1948.

I.c.46—Fluid Mechanics. R. C. Binder. Constable & Co. 1947.

I.d.11—Elasticity and Anelasticity of Metals. C. M. Zener. University of Chicago Press. 1948.

L.j.101—Air Survey. C. A. Hart. John Murray. 1948.

L.j.102—Aerial Photographs in Forestry. S. H. Spurr. Ronald Press. New York. 1948.

M.c.85—Microwaves and Radar Electronics. E. C. Pollard and J. M. Sturtevant. John Wiley & Sons. 1948.

N.a.99—Foundations of Modern Physics. T. B. Brown. John Wiley & Sons. 1949.

OO.126—Royal Society Scientific Information Conference. The Royal Society. 1948.

Q.a.193—Catalogue of Books in the Library. J. M. Fulford. British Scientific Instrument Research Association. 1949.

Q.c.61—Laboratory of the Air. John Pudney. H.M.S.O. 1948.

R.a.29—Interpretive History of Flight. M. J. B. Davey. H.M.S.O. 1948.
S.d.100—Perchance: A Short History of British Naval Aviation. B. J. Hurren.
X.b.162—The Aircraft Yearbook 1948. Aircraft Industries Association of America. 1948.

N.A.C.A. Technical Notes

1561—*Strength and creep characteristics of ceramic bodies at elevated temperatures. M. D. Burdick, R. E. Moreland and R. F. Geller.*
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Publications Scientifiques et Techniques du Ministere de L'air.

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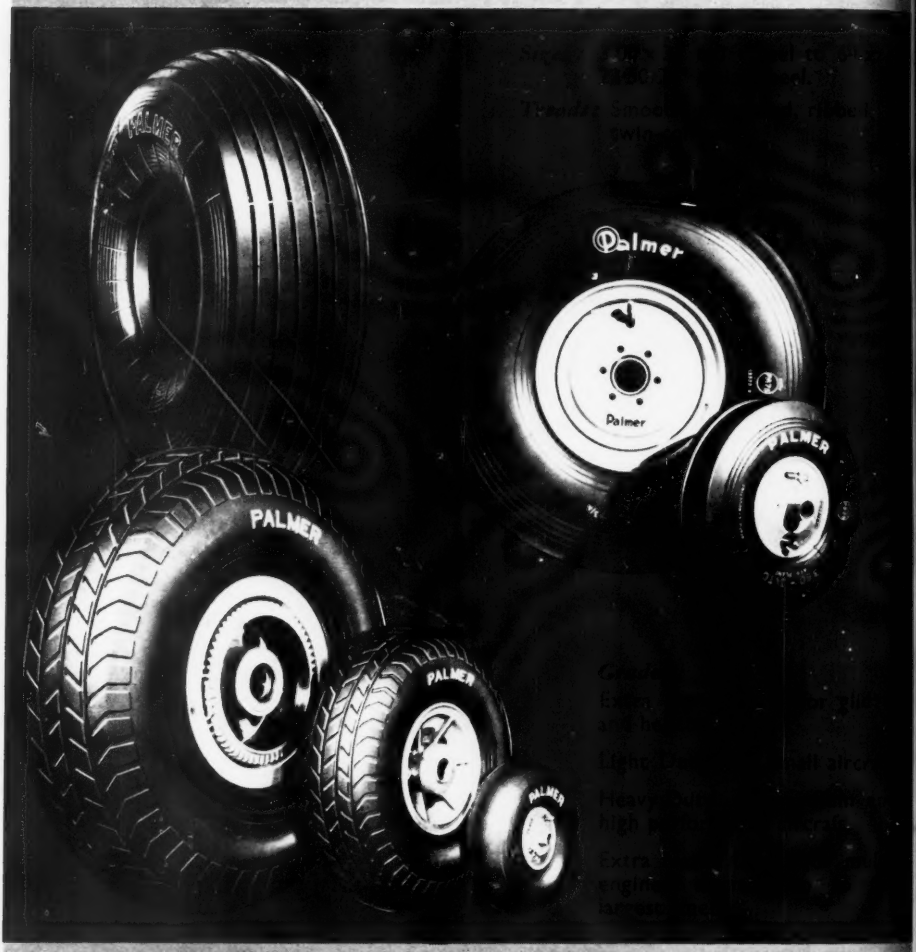

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